BEHAVIOR OF DIELECTRICS FOR SUPERCONDUCTORS

SYNOPSIS

A THESIS
SUBMITTED FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY
IN THE
FACULTY OF ENGINEERING & TECHNOLOGY

BY

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The discovery of high temperature superconductivity (HTSC) in 1986 sparked a fresh interest in research in this area so that they are put to industrial applications. Applications of HTSC in power equipments e.g. Generators, Transformers, power transmission cables, fault current limiters & magnetic energy storage will be maintained at the desired temperature 77-100 K by the use of liquid nitrogen [1-4].

Also solid insulating materials will have to be used as spacers. A predictable reliable long term dielectric performance of cryogenic dielectric structures is of crucial criteria for any power application [9]. The dielectric reliability of the cryogenic liquid (LN_2) is a prerequisite to this end. When solids in conjunction with the LN_2 are to be used high resistivity and a low loss index can become crucial with regard to low temperature cooling where any dissipated heat may lead to costly maintenance in terms of refrigeration.

Also it is important that the insulation components are identified, their behavior studied separately and in combination with each other so that a judicious & economical insulation system is designed [5, 6, 7].

In practical HTS devices liquid nitrogen (LN_2) and cryogenic nitrogen gas (CGN_2) plays a crucial role in applying HTS materials to the apparatus; both LN_2 and CGN_2 are used as not only a coolant but also an insulating material.

Due to this there have been extensive studies of electrical properties, such as dielectric breakdown of LN_2 and CGN_2 [8]. Since the cost of LN_2 is significantly lower than the cost of liquid helium, the LN_2 cooled devices offer many advantages to the utility industry.

Keeping the above in view this work is oriented towards designing & conducting experiments and analyzing results to arrive at conclusions which may be useful to designers using high temperature superconductors and LN_2 as main coolant and insulant.

In this report data available in literature has been reviewed and reported in Chapter 1.

In Chapter 2 the statement of the problem has been presented and it has been clearly brought out that there is a need to conduct a number of experimental studies, analyze the results to arrive at useful conclusions.

The experimental setup, sample preparation, temperature measurement, voltage measurement, measurement accuracy and other details for various experimental studies performed has been detailed in Chapter 3.

Chapter 4 deals with the results and the results include the following experimental study made for the assessment of:

I. Breakdown Voltage of liquid nitrogen and its dependence on various electrode configurations.

II. Breakdown strength of solid dielectrics in liquid nitrogen medium.

III. Loss index of solid dielectrics immersed in liquid nitrogen.

IV. Breakdown of cryogenic Air under Non-Uniform Fields

V. Area & Volume effects on the breakdown strength of LN_2

In Chapter 5 the analysis of results obtained in Chapter 4 are presented. Also an attempt has been made to correlate the loss index, volume resistivity with the breakdown voltage and an equation relating these parameters has been reported.

Finally in chapter 6 the summary of results obtained, conclusions made and the future work suggested has been reported.

It is envisaged that this work will finally help in the selection of insulating materials to be used along with high temperature superconductors. Further it is hoped that the equation obtained for the estimation of breakdown strength of materials dipped in liquid nitrogen will aid greatly to design engineers.

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CHAPTER-1

1.1 Introduction:

Superconductivity, with its unique property of zero electrical resistance at temperature approaching absolute zero was discovered for mercury in 1911 by K.Onnes [98]. Applications immediately became apparent despite the necessity of a low temperature environment. Unfortunately, it was quickly discovered that relatively small magnetic fields and small currents destroyed the zero resistance property; thus superconductivity remained a scientific curiosity, not a technology for 70 more years. However during those seventy years, important scientific advancements were made.

With the discovery in 1986 a new class of "High critical temperature Superconductors (HTS)" that operate at substantially higher temperature (although still cryogenic), remarkable progress has been made in advancing a broader use for superconducting technology. This discovery of superconducting materials that carried high currents in high magnetic fields generated much scientific and technological acclaim. Suddenly the dreams of a superconducting technology became possible [98]. Despite the availability of high performance low temperature superconducting (LTS) wires and continued advances in cryogenic refrigeration technology, the difficulty of obtaining such low temperatures severely hampered the deployment of low temperature superconductors in power technology [83].

Operating at temperatures from 30 to 80k, HTS open the door to highly simplified cryogenics and increased stability, which result in economic systems not feasible with low temperature superconductors [73]. The discovery of HTS renewed the interest in superconducting power transmission systems & motors and stimulated not only further investigations on HTS but also contributed to resumption in research on LTS in order to exploit the results achieved in the past years [57].

However whatever the applications that may arise, it will not be possible to use superconductors alone. They will inevitably be surrounded by insulating systems, either thermal, electrical or both combined [33]. Helium and nitrogen are excellent insulating fluids for classical LTS and HTS respectively. Many insulation systems in LTS applications are based on helium either in its liquid state or in its supercritical state [30, 44].

In practical HTS devices liquid nitrogen (LN_2) and cryogenic nitrogen gas (CGN_2) plays a crucial role in applying HTS materials to the apparatus; both LN_2 and CGN_2 are used as not only a coolant but also an insulating material. Due to this there have been extensive studies of electrical properties, such as dielectric breakdown of LN_2 and CGN_2 [32]. Since the cost of LN_2 is significantly lower than the cost of LHe, the LN_2 cooled devices offer many advantages to the utility industry. LN_2 insulated and cooled superconducting transformers are much smaller, have excellent capability for over capacity operation, upto twice the rated power, and are oil free, i.e. environment friendly [45].

It is observed that the liquid nitrogen can never be used by itself without being incorporated into a composite insulation system. So whenever a liquid dielectric is used as an insulant in electrical apparatus it is necessary to provide an insulating mechanical support to hold the conducting members at the required spacing. The space between the conductors is therefore bridged at some point by a solid dielectric [5, 74]. Hence, the HTS system may consist of metallic parts wetted by the liquid i.e. of bare conductors, of conductors covered by an insulating sheet, of wrapped insulating foils impregnated by the liquid, and of solid insulating spacers where the liquid/solid interfaces may be a very crucial region [74].

Electrical insulation used at ambient temperature are generally well known. They are gases, liquids and solids, either in composites or impregnated tapes. Fortunately they are the pillars for cryogenic insulants as well. However the introduction of an extremely low temperature environment (77 K for HTS) imposed additional electrical and thermal constraints on the insulation system, and thus requires a better understanding of the behavior of materials under combined electrical and thermal stresses at these temperatures. Therefore the dielectric insulation design of any superconducting power apparatus must be based on the available insulators in the cryogenic temperature domain [44].

Then for applications at very low temperatures, how much of the knowledge acquired at ambient temperature can be transposed; is partial discharge behavior a major concern for insulation operating at cryogenic temperature? What will be the constraints for various applications? Is there still ageing at 4K? these questions are absolutely fundamental and must certainly be addressed before any cryogenic application becomes a reality [33].

A lot of work has already been done to investigate various aspects of LN_2 and solid insulating materials at cryogenic temperatures regarding their electrical, mechanical, thermal, general properties, ageing effect and radiation resistance. Also subsequent experimentation with solid insulating materials dipped in LN_2 provides encouraging results. [106]

However, the focus in this research field is now shifting from fundamental to practical studies. HTS prototypes at commercial power levels have already been demonstrated, particularly power transmission cables and motors [76]. As a result it is strongly required to obtain design data for electrical insulation used in superconducting apparatus [32].

Even though there is already abundant knowledge about insulating materials at cryogenic temperatures and the feasibility proven, many laboratories in the world are continuing research to increase the knowledge and to fill in the remaining gaps. The thesis aims at providing to some extent a complete and comprehensive study made possible by experiments, analysis and critical examination so that HTS are used in electrical system with best possible life.

Before embarking upon the actual work and preparing a work plan for the desired study, a brief review of existing literature is presented in the text to follow.

1.2 Review of Literature

1.2(a) Some details of Low Temperature Superconductors

After discovery of superconductivity interest developed with respect to the possibility of using superconductors for the windings of magnets. The problem of loss of superconducting property of the materials in the presence of low fields persisted and success was delayed. But superconducting magnets became a reality in 1955 when Yntema [1] reported the operation at about 7 kgauss of an electromagnet having superconducting windings.

In 1960, Autler [2] reported the operation of a superconducting solenoid at 4.3 kgauss and was able to later increase the maximum field to about 10 kgauss.

In order to search LTS with high critical current density, G.D.Kniep and his group explored the possibility of increase in critical current density by proper combination of annealing and cold deformation of alloys. It was shown that a tenfold increase in critical current density was possible by short heat treatments of Nb-Zr superconductors [3]. Therefore it seemed likely that the critical current density may be increased in other alloy systems by similar heat treatments.

The property of superconductors of interest for magnets that has been most frequently studied is the maximum current carrying capacity (while in the superconducting state) as a function of applied magnetic field. These observations were usually made at temperatures that were accessible with the use of LHe (4.2 k), which is now an established cooling and insulating fluid for magnets using LTS [4].

The discovery of Nb_3Sn, which remains superconducting in magnetic fields exceeding 88 kgauss while carrying current densities in excess of 10^5 amp/cm^2 stimulated widespread activity directed towards the construction of superconducting magnets. Consequently superconducting magnets of Nb_3Sn and of Nb-Zr were constructed and tested by several laboratories.

The electrical insulations of superconducting magnets are closely related to their cooling method, and usually consist of solid insulating materials in combination with coolants such as He & LN_2. Therefore in designing insulation for any superconducting equipment, it is essential to consider the breakdown and other electrical characteristics of the coolants under various conditions.

J.Gerhold [25] reported the hypothetical concept of two different types of breakdown in LHe i.e. the low stress and the high stress breakdown. LHe breakdown could be assumed to occur within these two extreme limits. The high stress breakdown was correlated with the liquid density and did not depend on pressure. However the low stress breakdown had a strong dependence on pressure.

He pointed out further that actual breakdown was considerably influenced by the overall system conditions, similar to other liquids. Some of the breakdown parameters have been partly identified as electrode area and spacing, liquid purity, electrical field conditions, test procedure, liquid pressure and temperature, and electrode surface conditions. However, values from more than 100kV/mm down to less than 20 kV/mm have been reported for the liquid near the normal boiling point.

Though high stress breakdown appears very attractive for engineers but low stress breakdown does not have a negligible probability. This restricts the practical use of insulating LHe to low stresses down to 10 to 15 kV/mm at ambient pressure.

As reported by Gerhold [44] many researchers have investigated breakdown characteristics of cryogenic liquids. but most of them have focused only on static breakdown characteristics. Under practical operation of superconducting equipment, quench phenomena are unavoidable, so the quench of superconductors has to be considered for the insulation design, especially for superconducting fault current utilizing quench phenomena [59]. Quench phenomena causes thermal bubble disturbance in cryogenic liquids. resulting in degradation of electrical insulation performance.

Hao Fengnian etal [27] investigated the breakdown characteristics of vacuum insulation for the development of cryocables and other cryogenic electrical apparatus. They reported the influence of conditioning, pressure, gap spacing, electrode material and voltage wave shape on the breakdown voltage of vacuum insulation at room temperature and at cryogenic temperature.

The experimental investigations revealed that cooling the HV sphere electrodes by LN_2 enhanced the breakdown voltage of vacuum insulation. Further conditioning processes, pressure effects. effects of electrode material and separation had their effect in vacuum insulation at room temperature as well as cryogenic temperature. Thus for practical designs of low temperature HV vacuum insulation systems. it was suggested to utilize or directly use the experimental data of breakdown voltages obtained at room temperatures.

1.2(b) Liquid Nitrogen as insulating media for High Temperature Superconductors

Electrical properties of LN_2 and its vaporized gas became of interest with the discovery of HTS materials [113,115]. M.Hara etal [26] studied the breakdown characteristics of gaseous nitrogen from room temperature down to 74k. The investigations revealed that with uniform field gap geometry, validity of Paschen's law is confirmed under the saturated gas conditions at 74k. Earlier Fujita etal had reported that this law held down to 93k at a constant gas density

However in practical apparatus, nitrogen gas will coexist with LN_2 surface and then will be in the vapor mist mixture condition. To elucidate the mechanism of discharge and dielectric breakdown under coexistence of LN_2 and CGN_2 in practical conditions H.Goshima etal [32] measured dc dielectric breakdown characteristics of cryogenic nitrogen gas above LN_2 surface for needle to plane and sphere to plane electrode configurations. The investigations revealed that dc breakdown voltage of CGN_2 increased with decreasing distance to the LN_2 surface measured from the gap axis. The breakdown voltage proved to be enhanced not only by the temperature drop of nitrogen gas due to the existence of LN_2, but also by an effect of vapor mist arising from vaporization of LN_2. Further for the quasi-uniform electrodes, the breakdown voltage characteristics agreed well with the Paschen curve for cryogenic nitrogen gas by taking into account the decreased temperature and the vapor mist density [32].

In some of the superconductor applications, where the superconducting coils are immersed directly in LN_2 coolant, which is also an insulant, the liquid is stressed. Losses arising from operating stresses, in addition to influencing the insulating properties of LN_2, also act as load on refrigerators used to cool the equipment. Therefore it becomes imperative that the dielectric losses are kept low in working stress region and to understand the dielectric loss behavior of LN_2 under a variety of conditions to estimate its magnitude as well as to understand the mechanisms contributing to it.

Dielectric loss (tanδ) measurements for cryogenic fluids, particularly for LN_2 there exists a wide spread in the reported values of tanδ [51-54]. Sometimes high losses have been reported in LN_2 [50]. Electrode surface conditions and impurities are expected to be the cause for these variations in the measured results at high fields. In addition in practical conditions air that exists along with LN_2 can influence the dielectric losses to a greater extent due to moisture and oxygen condensation.

M.Nagao etal measured the dielectric loss in LN_2 under different conditions. The investigations revealed that the losses in commercial pure LN_2 were well under acceptable range for practical applications ($<5x10^{-4}$). Since LN_2 consists of non-polar molecules it is expected that the dielectric losses be in the negligible range. Further the authors reported no significant effect on measured losses due to the presence of dry air. Some high values of tanδ measured were thought to be resulting from presence of ice or other solid impurities [50].

In another study of dielectric loss behavior of liquid nitrogen it was reported that LN_2 exhibits very low but measurable dielectric loss of the order of $\tan\delta = 10^{-5}$, at power frequencies, and that this loss was not intrinsic to the liquid but attributable to impurities or fine ice particles. Further it was inferred that the contribution to loss at low stresses appears to come from ionic conduction as well as interfacial polarization; and that at high stresses appears to be due to charge injection from electrode surfaces [60].

According to a survey of superconducting coil failures and accidents, some causes of severe failures were suspected to be due to conducting particles, which got accidentally introduced into the electrical insulation space. Even during fabrication and operation of a superconducting apparatus it is possible that dielectric as well as conducting particle contaminants can intrude into the insulation space of the apparatus. Conducting particles that are hazardous to electrical insulation can be metallic particles produced during fabrication of superconducting coil as well as the cryostat vessel or carbon particles introduced from the filter with coolant during operation. M.Hara etal studied experimentally dc pre-breakdown phenomena and breakdown characteristics in the presence of free conducting particles in LN_2. The investigations revealed that a micro discharge occurs when charged particle is approaching an oppositely charged electrode. An intense micro discharge can trigger a complete breakdown of the gap. Comparatively the breakdown voltage of a uniform field gap with free metallic particle of mm size might be reduced well below that of a point to plane gap without a particle in LN_2. However it was found that carbon powder is less hazardous compared to metallic powder [72].

1.2(c) Solid insulants in Liquid Nitrogen

As mentioned earlier, whenever a liquid dielectric is used as an insulant in electrical apparatus it is necessary to provide an insulating mechanical support to hold the conducting members at the required spacing. It is known that the solid insulation surface and electrode (conductor) interface is a weak point electrically. Therefore it is of considerable practical importance to gain more knowledge of the reasons for the weakness of the insulation at the solid-liquid interface and its effect on the total performance of the system.

James etal [5] conducted experiments and concluded that the solid supports between uniform field electrodes in nitrobenzene distort the electric field in the gap. It was also observed that the degree and location of the distortion depended upon the electrical properties of the solid. However the results indicated that the liquid does not predominantly influence the field distortion and therefore it may be possible to apply the results directly to any insulating liquid of high purity and low ion content.

Jon W.Swanson etal conducted research [14], with the objective to determine if a relationship could be found between dielectric strength and other properties of electrical insulating materials on an empirical basis by using variables predicted by basic theory. They were successful in correlating dielectric strength of the materials under consideration as a function of its volume resistivity, dissipation factor and dielectric constant. It may be pointed out here that a similar study is possible in the case of solids dipped in LN_2.

1.2(d) LN_2 as insulation in Superconducting cables

The cost of underground cable systems utilizing conventional paper-oil as insulation can be as high as twenty times the cost of comparable overhead lines [7]. Further heat dissipation problems in oil filled cables intensify as the voltage is increased above 345 kV due to high dielectric loss and increased thickness and recourse to artificial cooling is made. Power throughput may be increased in high-pressure oil filled systems by circulating the oil through the enclosing pipes.

The severity of the problem of increasing the capacity of cable systems to meet the future power levels is such as to make the investigations into alternative coolants and dielectrics worthwhile. A possible alternative is some form of cryogenic cable [8,77] of which there are two types:

- Cryoresistive cables at 77 K
- Superconducting cables

Many of the dielectric problems encountered in the design of a cryoresistive cable are likely to be encountered in the design of a superconducting cable and thus work on the former will be useful to both types of cable. With this vision, B.M.Weedy etal investigated the evaluation of possible insulation systems for cryoresistive cables operating at 77 k [6].

There are three possible forms of dielectric available for cryoresistive cables:

1. Vacuum: probably resulting in a rigid cable with spacers.

2. Use of cryogenic fluid, which results in rigid cable with spacers.
3. Tapes impregnated with cryogenic fluid, forming a composite insulation of the same form as in conventional oil filled cables. This arrangement gives a flexible cable with smaller number of joints.

The authors investigated the effect of the following in lapped tape liquid nitrogen composite dielectric:

- LN_2 pressure on the breakdown strength of various taped dielectrics
- Tape thickness on the breakdown strength
- Tape thickness and hydrostatic pressure on the discharge inception stress
- Dielectric loss

The authors postulated the following tentative hypothesis for the above said investigations with a rider that further work is necessary to complement and clarify the mechanisms occurring in a lapped tape liquid nitrogen composite dielectric:

- The breakdown strength of a material is probably a function of its discharge resistance. Pressurizing the liquid suppresses the discharges and for discharge resistance materials, increases the breakdown strength. Whereas the breakdown strength of some materials is pressure dependent, that of LN_2 is much more so and thus the breakdown strength of the composite is overall a function of liquid pressure.
- Tape thickness influences the breakdown strength of lapped dielectrics and this phenomena is material dependent. Thus if a graded dielectric is to be

employed, the effect of thickness would have to be measured for the particular material considered.

- Discharge takes place in gas bubbles in the LN_2 in the butt gaps. Bubbles in the LN_2 should be completely suppressed if a high operating stress is required, or the dielectrics will have to be kept at a stress well below the discharge inception stress. This latter procedure would probably result in too large thickness of insulation. Simply pressurizing the liquid nitrogen does not suppress all the bubbles. Sub cooling and then pressurizing may suppress all the bubbles, but this must be determined experimentally.
- *Dielectric loss alone is not a sufficient criterion for selecting a suitable* dielectric. The mechanical properties of the tapes must also be considered; for it may appear unsuited for use in cable lapping machines.

The design of Superconducting transmission cables requires a system approach, which includes consideration of the conductor, insulator, cryogenic envelope and refrigerator. Each component of the system must function satisfactorily without disrupting the other system elements. The cable insulation should not burden the refrigerator with a heat load due to ac dielectric losses. Loss tangent is the parameter, which ultimately determines the suitability of insulating materials in regard to refrigeration load.

For this reason cable designers [10] placed an upper limit on the tanδ of taped insulation somewhere between $4x10^{-6}$ and $20x10^{-6}$. In rigid cable design it is possible to use LHe as the insulator [9]. Solid dielectric spacers however must be used to keep the inner and outer conductors concentric. These spacers are allowed to have loss tangents more than an order of magnitude higher than taped insulation because the spacers are but a small fraction of the total volume of insulation. Nevertheless, reliable values of loss tangent for spacers are useful to the design engineer.

M.Kosaki [37,82] reported comparison of some aspects of electrical insulation characteristics between composite insulation and solid insulation design. Though the composite insulation is superior to solid insulation with respect to capacitance and dielectric loss because the cryogenic fluids have a lower permittivity than the solid insulation, the loss tangent of polymers in the cryogenic region is significantly smaller than that at room temperature (order of 10^{-4} or less).

Generally speaking the electrical breakdown strength increases in the cryogenic region, which is a favorable situation for the electrical insulation of superconducting cable for both composite and solid insulation.

A solid insulation design using polymers can provide the potential for the total elimination of partial discharges. PD deterioration need not be considered if the solid is free from defects, because polymers contract noticeably when cooled down to the cryogenic temperature region and inadvertently introduced voids are squeezed out. Therefore, if cooled down to the cryogenic temperature, there is hardly any space for PD to occur in extruded polymer insulated cable. However, if PD occurs in the butt gap at cryogenic temperature, deterioration may proceed more malignantly than in the case encountered at room temperature [82].

P.Chowdhuri [22] performed the dielectric studies as part of the dc Superconducting power transmission line program and reported that impregnation of cellulose and copaco papers (rag paper) and PP/C (polypropylene-cellulose paper) with mineral oil improved their dc withstand strengths, significantly, even at cryogenic temperatures. In yet another study of the similar kind a HTS dc transmission cable prototype was designed to carry 10,000 A at 40 kV. At an operating temperature of 31 k the prototype cable had a current capacity of 11067 A (the largest dc current reported in high temperature prototype at that time) that represented a tenfold increase in current over a conventional 1000 mm^2 copper cable [36]. This result was indeed promising first step towards the transmission of dc energy using force cryocooled superconducting cables.

Hiroshi Suzuki etal [29] investigated the dielectric properties of LN_2 impregnated synthetic insulation system considered to be promising for use in HTS cables and proposed the design stress for 66 kV cable. It was found that the ac breakdown strength of cellulose paper, polypropylene laminated semi synthetic paper (PPLP) and biaxiallyoriented polypropylene laminated paper (OPPL) were almost the same. Further it was found that the decline of the thickness dependence of the breakdown strength of the LN_2 impregnated insulating cable is steeper than that of the oil filled cable.

The authors reported operating stress to be 10.9 kV/mm for 66 kV cable with 4mm insulation thickness and suggested to design the 66 kV cable with insulation strength of 10 kV/mm.

A number of HTS cable designs have been developed to take advantage of the benefits of superconductivity, while minimizing the additional capital and operating costs that result from the material and refrigeration requirements [85]. At present, there are two principal classes of HTS ac power cables under development [96].

The first design employs a single conductor with HTS wires stranded around a flexible core in a channel filled with LN_2 coolant. This design employs an outer dielectric insulation layer at room temperature and is commonly referred to as a warm dielectric design [97]. In the warm dielectric cable, the LN_2 coolant is used only to maintain the cable at the appropriate operating temperature, and is not used as part of the cable insulation system. Further in warm dielectric cable, conventional XLPE is used for electrical insulation. Thus the insulation design techniques established in XLPE cable can be applied [80]. This design was mainly meant to retrofit existing pipe type cables to increase the power transfer capacity of the circuit by a factor of approximately two and was targeted for practical applications in Denmark and USA [40,45,46]. Because the design has the single conductor, generally it requires fewer superconducting tapes than the cold dielectric design (the other design). Further this design uses proven dielectric materials and has accessories derived from conventional designs therefore it requires similar installations and handling procedures as a conventional cable.

The primary disadvantage of this design is its relatively high losses caused by the lack of an HTS shield; thus requiring cooling stations at closer intervals compared to other HTS cable designs. Also it has difficulty in reduction of cable diameter.

The second design employs two concentric layers of HTS wire separated by a cold dielectric and is commonly referred to as cold dielectric (CD) design. LN_2 coolant may contact both layers, providing both cooling and dielectric insulation between the center conductor layer and outer shield layer.

Compared to the warm dielectric design, it has reduced ac losses, a higher current carrying capacity and is appropriate for higher power ratings. The key benefit to the CD design is the superconducting shield layer, which is wound directly over the cryogenic dielectric. The shield contains the magnetic field generated by the phase conductor, thus eliminating losses due to magnetic coupling with adjacent cables or metallic objects.

This design can have two forms, one with three conductors enclosed in a single cryostat system, which can reduce the diameter of HTS cable and replace conventional XLPE and oil filled cables by CD HTS cable.

The other design could be with all three conductors equipped with their own cryostats. Current density in excess of 200 kA/cm^2 are sought for this design and when attained would allow not only an increase in transmittable power but also a reduction of transmission voltages. Cold dielectric insulation system can be of the tape [6,13,18-20,47] or the extruded dielectric type [37,48].

Regarding long-term deterioration of the dielectrics under cryogenic temperature, as mentioned earlier, one has to pay little attention to the chemical and thermal ageing; only the PD can be considered main cause of the deterioration. Butt gaps in taped insulation can be source of PD's whereas extruded CD could be discharge free [37, 80]

For the realization of CD cable, the choice of an optimized insulation system, with properties that are best compromise between physical-electrical characteristics and design requirements are important. To this purpose a specific study was planned by F.Ombello etal [81] to qualify different materials. On the basis of literature results, mostly carried at LHe temperature, PPLP, high-density polyethylene (HDPE) fiber and EPR were chosen as potential candidates for the final use in LN_2. Electrical properties were evaluated and compared by means of different models (oil impregnated). Short term and long term tests were carried out at LN_2 temperature and at different absolute pressures for the evaluation of electrical endurance. The investigations revealed that PPLP shows the best behavior among the considered materials, for the application at cryogenic temperature in a superconducting cable.

1.2(e) <u>Loss index and Partial Discharge in LN_2 insulation</u>

J.Gerhold [44] reported the loss index and some physical parameters for materials of special interest in cryogenics. The loss index for different dielectrics were compared at 4.2k, 80k and those obtained under atmospheric conditions. The author has also reported contraction of the materials from room temperature to cryogenic temperature.

The failure of the insulation of high voltage equipment often arises from the action of electrical discharges in internal gaseous cavities. Internal discharges can cause deterioration and eventual failure of the insulation.

T.Tanaka in 1977 started a study of the macroscopic behavior of internal discharges in LN_2 and some of their effects on solid insulation. It was found that a spun-bonded polyethylene system was inadequate once tiny internal discharges take place [12]. Discharges in LN_2 tend to be suppressed by an increase in pressure. It was shown, however that internal discharges are likely to happen near the boiling temperature even though LN_2 is pressurized [13].

The author has also reported internal discharge phenomena in a LN_2 filled cavity under an ac impulse voltage [11]. The authors investigations suggested that discharges in LN_2 are likely to be localized in the first half cycle of the ac impulse i.e. the effective discharge area is reduced by increasing pressure. In the subsequent cycles, the discharges are affected by the bubbles formed during the preceding cycles.

To achieve a satisfactory working life of the insulation and to increase the working stress, it is necessary to prevent the formation of cavities. Badran etal [16] have shown that both repetition rate and the magnitude of discharges that occur in air filled cavities in paper insulation under direct voltage conditions increased as the temperature is raised above ambient. As a consequence the electric strength is decreased. The author has attributed this behavior to the reductions in volume and in surface resistivities of the insulation that take place at elevated temperatures and consequently expected that the repetition rate and the magnitude of the internal discharges might decrease at low temperatures with a corresponding increase in the electric strength.

B.Salvage [15] etal investigated the internal discharge phenomena in artificial air filled cavities in impregnated-paper, polyethylene and polypropylene over a temperature range from 90 to 343 k. The analysis of the result revealed that when the temperature is lowered, the discharge repetition rate and the discharge magnitude are considerably reduced, and the electric strength of the insulation is correspondingly increased as expected, the improvement being more prominent with the direct voltages.

R.J.Denseley etal [18, 45] reported the short term PD and electrical breakdown characteristics of some film type and fibrous materials and their laminates immersed in LN_2. The group studied the PD inception and extinction voltages, distribution of their magnitudes and repetition rate in the various specimens with and without artificial cavities at pressure upto 0.4 Mpa. The results emphasized the relative roles played by the gas bubbles inside the cavity and the structure of the material. The investigations also revealed that use of laminates in cryo-insulation; such as polypropylene/cellulose paper show promise as such a laminate combines the good impregnation of the cryogenic fluid arising from the porous material and the high breakdown strength of the film.

Also A.Bulinski & J.Denseley [19] reported the results of an investigation in which they determined the lightning (1.2/50 μs) and switching impulse (250/2500 μs) strength of Nomex, Tyvek and PPLP and how various parameters like effect of repeated impulses of constant amplitude, hydrostatic pressure & polarity reversal affected these breakdown strengths.

Masazumi Shiraishi etal [21] studied the pressure dependence of dielectric breakdown in LN_2 from the viewpoint of the suppression of the bubble formation by applied voltage. The investigations revealed that for the constant gap length, the breakdown voltage increases with increasing pressure and saturates at around 10 atmospheres whereas for shorter pulse width, the increase in breakdown voltage with pressure becomes less remarkable. In a non-uniform field of a plane-needle electrode system, the breakdown voltage of the negative needle configuration increased remarkably with increasing pressure but that of positive needle was almost insensitive to the pressure. The authors interpreted the results in terms of the suppression of the formation & the development of gaseous bubble in the breakdown of LN_2 under high pressure and at short pulse width. The strong pressure dependence of the negative needle configuration indicated that the bubble formation due to electron injection from the cathode and its development are suppressed at high pressures whereas in the positive needle configuration the small pressure dependence shows that the breakdown is not initiated by the bubble formation by an electronic process even for the μs range width.

As mentioned earlier, it is generally agreed that ageing of electrical insulation at low temperature is mainly the result of PD activity, which results in a reduction of the insulation life caused by a slow and progressive erosion of the insulating material and in heat generation. It induces localized thermo-mechanical stresses sufficiently large to fracture the dielectric [31].

Kosaki [37] in his view on ac superconducting cables, pointed out that extruded polymeric insulation performs adequately well in the presence of PD, though he did not attempted to analyze the PD data as concerns the variation of the apparent charge as a function of the temperature and electrical stress.

M.Hazeyama etal [78,79] studied PD inception characteristics in LN_2/polypropylene laminated paper composite insulation system for HTS cable. The aim of the study was to know about the PD inception characteristics as influenced by the butt gap volume in LN_2/solid insulation system. Investigations revealed that the PD inception electric field strength (PDIE) depended on the volume of the butt gap because of the increasing probability of weak points of electrical insulation, and PDIE linearly decreased with increasing stressed volume of the butt gap in the log-log scale.

For the optimization of electrical insulation design for HTS cable, evaluation of electrical insulation characteristics especially for butt gap of LN_2 impregnated cold dielectric, which consists of the wrapped tape insulation, impregnated with LN_2 plays an important role. Hiroshi Suzuki etal [80] reported the PD inception and breakdown characteristics in LN_2 impregnated butt gap model which modeled a weak point of the wrapped tape insulation impregnated with LN_2 and cable model with short length with PPLP, Nomex paper and cellulose paper.

B.M.Weedy etal [17] reported that life expectancy-stress relationship, V^nL = constant; is valid for a wide variety of polymer tapes in cable model configuration. Further the author has reported that life exponent n is strongly dependent on the pressure of the LN_2 impregnant, and tests at high pressures give considerably smaller values of n than tests at atmospheric pressures..

However Weedy suggested that further work on the extinction of discharge produced by transient over voltages is necessary before life tests can be used with the confidence to calculate the working stress of a cryogenic cable.

A.Bulinski etal [20] in their investigation showed that the impulse and switching surge characteristics of cryogenic insulation becomes important if the exponent n of the life equation is greater than a critical value. Thus, it is not necessary to find n precisely but to verify that it is larger than the critical value. The results presented confirmed that n is usually greater than 20 for cryogenic insulation.

T.Tanaka [24] while investigating the characteristics of composite insulation reported the V-t characteristics for LN_2 impregnated insulation, which are divided into two regions. The value of exponent n of the life equation ranges from 50 to 100 in the first region, whilst it is 5 to 10 in the second region.

There have been extensive studies of dielectric properties such as the breakdown voltage of LN_2. Nevertheless, most of the data on the electrical breakdown of LN_2 have been obtained under limited experimental conditions, such as sphere-to-sphere electrodes with a small gap and relatively low voltage levels. H.Goshima etal conducted experiments to obtain some design data for electrical insulation used in superconducting apparatus. The group investigated area and volume effects on breakdown strength in LN_2. Their results revealed that both area and volume effects, having a mutual correlation, simultaneously lead to the degradation of the breakdown strength in LN_2. Further in cryogenic fluids, micro-protrusions on the electrode surface and thermal bubbles in the space gap may be regarded as main weak points for the area and volume effect respectively. Consequently the authors pointed out that it is important to consider both thermal bubbles and electrode surface condition for HV insulation of superconducting power apparatus [28,34-35,39].

1.3 Applications of High Temperature Superconductors

The long awaited marriage of superconducting with electric power has undergone a lengthy engagement to say the least. The types applications in which superconducting has the potential to be effective in an electric power system can be separated into two general classes. The first type includes those technologies in which superconducting is simply a replacement of existing resistive materials, for example cables, motors, generators and transformers [111]. The second type includes technologies that will be enabled by superconductivity and that have little or, at most, limited capability if conventional resistive or other materials are used. Examples are superconducting magnetic energy storage (SMES) and large fault current limiters (FCL).

The studies referred to earlier have made it possible to go for commercial production of superconducting magnets [75, 98,117], superconducting generators [71, 83,98,105], superconducting motors [64,73,83,98], superconducting magnetic energy storage [38,62-63,66,68,83,85,92-93,95], superconducting fault current limiters [38,63,70,83,85,94,98], superconducting cables [36,41-

43,49,55,69,73,83,85, 98-104,110,114] and superconducting transformers [61,66-67,73,83,85-91,98,112].

Now it is possible to develop an all-superconducting substation today [65]. Superconducting transformers and cables will form the heart of the all-superconducting substation of the future. The all-superconducting substation can provide further advantages to the electric power system of the future if it incorporates other superconducting devices. For example, SMES units and FCLs can be integrated into the system. Further FCL can be closely integrated with the superconducting transformers.

These events plus a renewed and growing worldwide demand for electric energy, give hope that the final vows will actually take place during the first quarter of the coming century.

CHAPTER-2

STATEMENT OF THE PROBLEM

Statement of the Problem

A critical examination of the literature reviewed in Chapter 1 reveals that in most of the prototypes of HTSC based electrical apparatus, developed so far, LN_2 is used not only as a coolant but also as an insulating medium [34]. Before embarking upon commercial utilization of LN_2 as an insulator for HTSC, it is imperative that its electrical properties, particularly breakdown voltage under different electric fields, and its behavior as a component of a composite dielectric and other properties such as loss index are studied in detail.

Whenever a liquid dielectric is used as an insulant in electrical apparatus it is necessary to provide an insulating mechanical support to hold the conducting members at the required spacing. The space between the conductors is therefore bridged by a solid dielectric [5]. So the total behavior of the insulation system will be decided by the behavior of solid insulation in conjunction with liquid nitrogen.

Therefore, the breakdown mechanism of the solid insulators that are currently being used at room temperatures is also to be examined at temperatures of the order of 100 K in terms of their physical, electrical, mechanical and thermal properties so that their viability to be used as spacers or for providing mechanical support and insulation for HTSC based systems can be determined.

In designing superconducting electrical apparatus, the knowledge of cryogenic gas and LN_2 insulation characteristics is almost essential. The 50 Hz breakdown voltage in air at room temperature and air at cryogenic temperature under uniform field conditions has been reported earlier [76,106-108]. However, when non-uniform field conditions exist, it should be possible to evaluate the breakdown voltage using the breakdown voltages under uniform field conditions and vice-versa.

Though studies have been carried out under uniform as well as non-uniform field conditions using different dielectrics at cryogenic temperature [76,106-108], it seems that little efforts are made to correlate these results.

It has been reported earlier that the breakdown strength in SF_6 gas or transformer oil decreases with increasing electrode surface area or volume subjected to high electric stress [35]. The area and the volume effects of SF_6 gas or transformer oil have been statistically taken into account in the practical design of electrical insulation. However limited literature is available as regards to such studies and designing of practical insulation for superconducting devices using LN_2.

Keeping the above in focus a number of experimental studies were planned and carried out to derive useful inferences. The details of the experimental work done is as follows:

1. Breakdown voltage of LN_2 and its dependence on various electrode configurations for small gap lengths.
2. Breakdown strength of different solid dielectrics under uniform field conditions in air at room temperature and when immersed in LN_2.
3. Breakdown of cryogenic air under non-uniform fields at room temperature and at cryogenic temperature.
4. Loss index of different solid dielectrics in air at room temperature and when immersed in LN_2.
5. Area and volume effects on breakdown strength in LN_2.

The proposed work also includes the detailed analysis and formulation of results together; correlating relative permittivity ξ_r, dissipation factor $\tan\delta$, volume resistivity ρ and thickness t with the breakdown voltage of solid insulating materials at low temperature and arrive at a relation

$$\mathbf{BDS = f(\xi_r, \tan\delta, \rho, t)}$$

It is expected that the study and data presented in this thesis will provide an understanding of the dielectric properties of insulants for HTSC, at cryogenic temperature in LN_2 medium.

It is envisaged that the work will lead to fixing the desired characteristics and finally will help in the selection of insulating materials to be used for insulating high temperature superconductors.

The studies listed above are presented in detail in the subsequent chapters3-5. The experimental setup and the procedure followed have been discussed in Chapter 3.The results of these experiments have been analyzed discussed and presented in Chapters 4&5.

A summary of the results, conclusions and a brief discussion of possible future work have been given in the chapter 6.

CHAPTER-3

EXPERIMENTAL-SETUP

AC BREAKDOWN VOLTAGE IN LN_2

3.1 AC breakdown voltage in LN_2:

As stated in chapter 2 (Statement of the Problem), measurements were made to assess the ac breakdown voltages in LN_2 with different electrode configurations such as sphere- sphere, sphere-plane and other configurations with different gap lengths.

The various electrode configurations used simulated uniform, quasi-uniform and divergent field conditions for the assessment of ac breakdown voltages in LN_2.

3.1.1 *Electrode preparation:*

Various electrode geometries used for the breakdown voltage measurements in LN_2 are illustrated in Figures 3.1 & 3.2(a). The following combinations of electrodes were used for obtaining the breakdown voltage of LN_2 with gap lengths varying from 1 to 5 mm:

1. Sphere – Sphere
2. Plane – Plane
3. Hemisphere – Hemisphere
4. Needle – Needle
5. Sphere – Plane
6. Sphere – Hemisphere
7. Needle – Sphere

8. Needle – Plane

9. Hemisphere – Plane

10. Needle – Hemisphere

The electrodes used in the above experiments were made of brass. They were polished, buffed and cleaned with benzene and ethanol. While handling care was taken to keep the electrode surfaces untouched and free from scratches, dust and other impurities. The electrodes were mounted horizontally in a cryostat vessel as shown in Figure 3.2 (b) and were cleaned and dried before each set of measurements.

3.1.2 *Voltage source & measurement accuracy:*

The applied voltage was 50 Hz. ac obtained from 150 kV, 30 kVA testing transformer that is discharge free up to 100 kV. The breakdown voltages were measured with an accuracy of ± 3%.

3.1.3 *Treatment of the cryostat vessel:*

Initially, the cryostat vessel used for the above experiment was cleaned with LN_2. After a thorough cleaning, the cryostat was filled with LN_2 of 99.9% purity until the electrode assembly was completely submerged in LN_2 as shown in Figure 3.2(b). Measurements were initiated only after bubbling in the LN_2 completely stopped and the temperature of the liquid in the cryostat stabilized.

3.1.4 *Temperature measurement & measurement accuracy:*

The temperature was measured using a Chromel-Alumel thermocouple, which is suitable for a temperature range of $-200^{o}C$ to $1370^{o}C$ with an accuracy of $\pm 0.1^{o}C$.The-measured temperature of liquid nitrogen was 88 K.

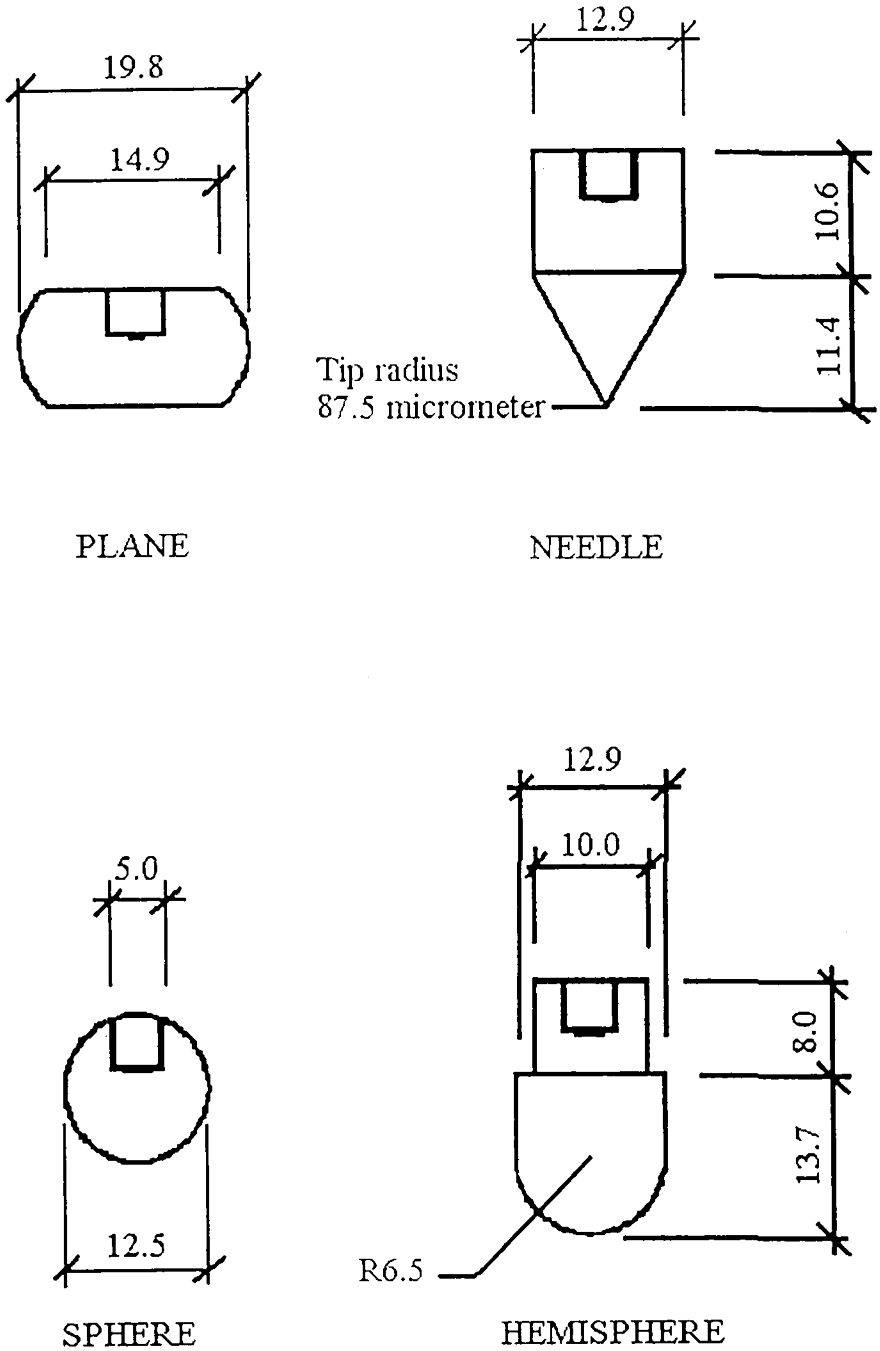


Figure 3.1. Various electrode geometries for breakdown voltage measurement in LN_2 (dimensions in mm)

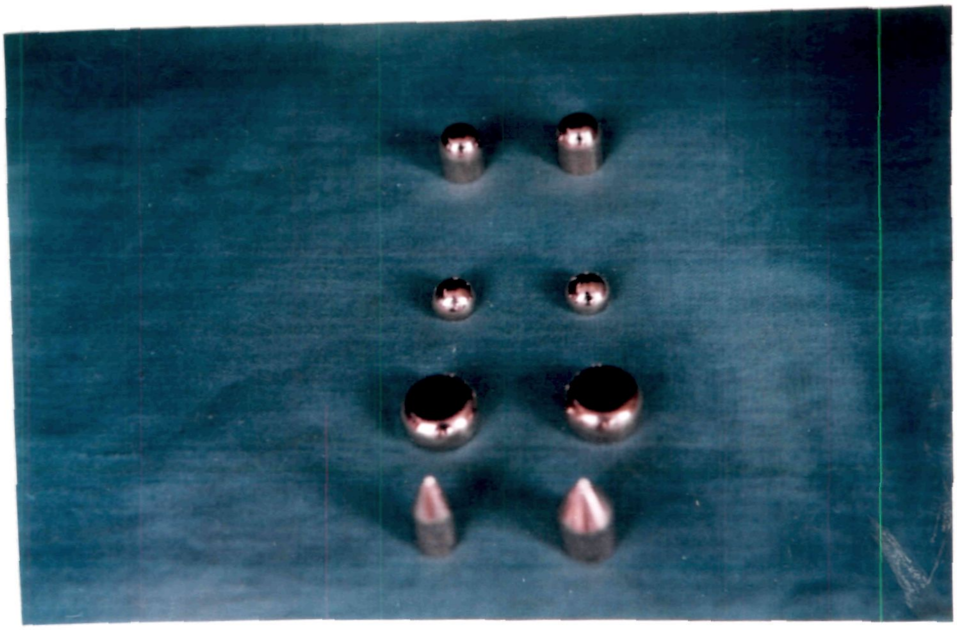


Figure 3.2(a) Electrodes used

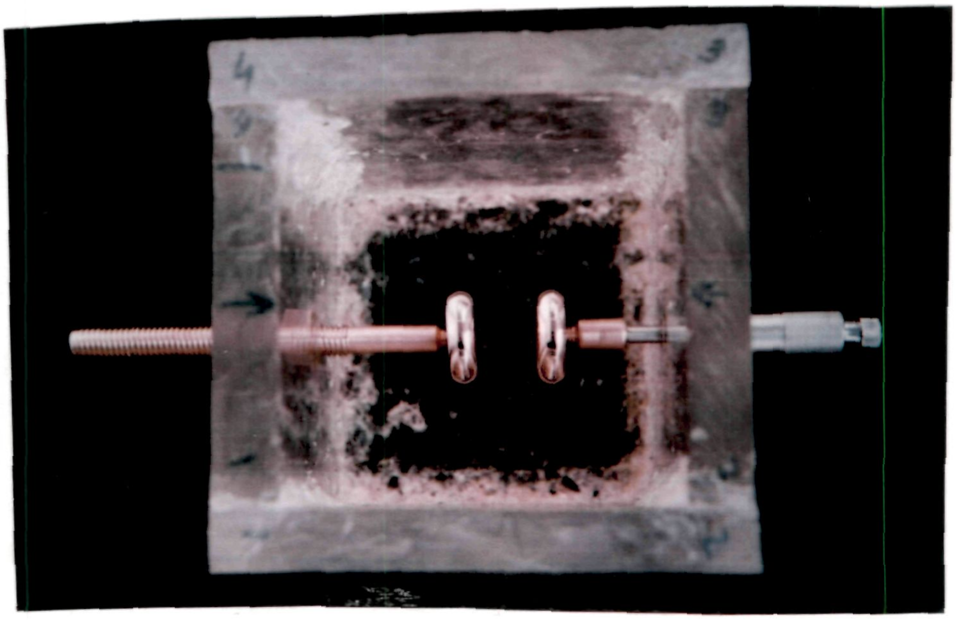


Figure 3.2(b) Cryogenic Vessel

BREAKDOWN STRENGTH OF SOLID DIELECTRICS DIPPED IN LN_2

3.2 Breakdown strength of solid dielectrics dipped in LN_2:

In order to investigate the effect on breakdown strength of solid insulating materials under liquid nitrogen environment, a sphere- sphere electrode configuration was used. The same set of configuration was used to obtain the breakdown strength of solid insulating materials under atmospheric conditions as well.

3.2.1 *Sample preparation:*

The following solid insulants were cut into a circular shape of 12-mm diameter:

1. Cotton Tape
2. Empire Tape
3. Kraft Paper
4. Polyester Film
5. Leatheroid Paper
6. Tyvak
7. Varnished Paper
8. Bakelite
9. Mica Sheet
10. Minimax
11. PVC Tape

12.Perspex

13.Cable PVC

14.Pressboard

15.Crepe Paper

16.Polythene Coated Paper

The insulants were broadly classified into cellulosic dielectrics, non-cellulosic dielectrics or a combination of the two. Non-cellulosic dielectric samples were used without any treatment. Cellulosic solid dielectrics used as samples were treated under vacuum (133 Pa) at 100^{o}C, for 48 hours. The sample thickness was measured at some randomly distributed 20 points, spread all over the sheet area with a micrometer having a least count of 0.01mm. The average of the 20 measurements was taken as the average thickness of the sample.

3.2.2 *Electrode preparation:*

Figure 3.3 shows the schematic of a sphere-sphere electrode configuration mounted in a cryostat vessel with the test sample sandwiched between them. Both the spherical electrodes were made of brass and were 12.5 mm in diameter. They were polished, buffed and cleaned with benzene and ethanol. While handling care was taken to keep the electrode surfaces untouched and free from scratches, dust and other impurities. The electrodes were mounted horizontally in a cryostat vessel and were cleaned and dried before each set of measurements.

3.2.3 *Voltage source & measurement accuracy:*

Same as described in Section 3.1.2

3.2.4 *Treatment of the cryostat vessel:*

The same treatment was given as described in Section 3.1.3

3.2.5 *Temperature measurement & measurement accuracy:*

Same as described in Section 3.1.4

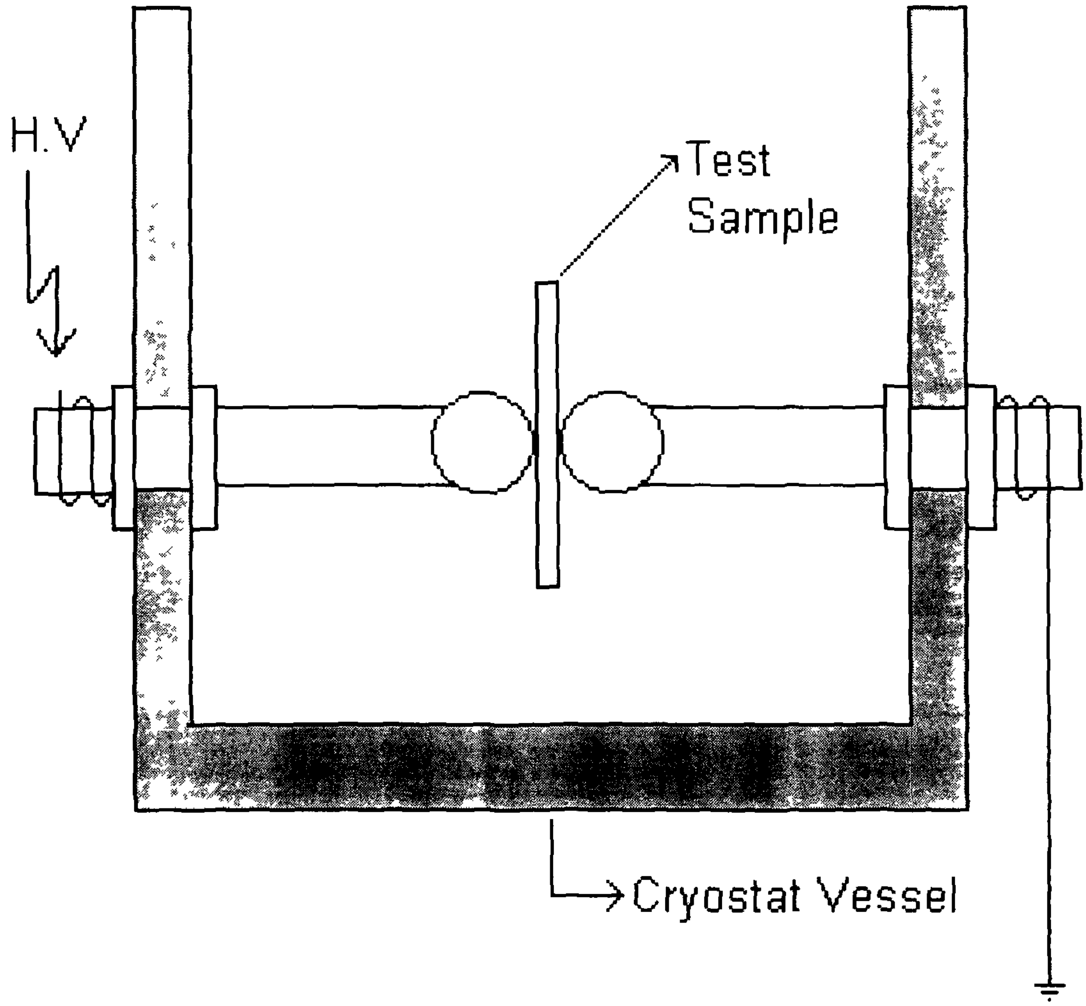


FIGURE 3.3

BREAKDOWN OF CRYOGENIC AIR UNDER NON-UNIFORM FIELDS

3.3 Breakdown of cryogenic Air under Non-Uniform Fields

As mentioned earlier in most of the prototypes of high temperature superconductor based power equipments, LN_2 has been used as a coolant and insulant to maintain the temperature of high temperature superconductor at about 77 K. In practical apparatus cryogenic gas will coexist with LN_2. Therefore, the knowledge of gas characteristics at cryogenic temperature is essential.

Keeping the above in view, experiments were designed to measure the ac breakdown voltages of air at room temperature as well as at cryogenic temperature under non-uniform field conditions using coaxial cylinders of different dimensions.

3.3.1 *Electrode preparation*

Figure 3.4(a) shows the schematic of the coaxial cylinder electrode configuration used. The outer conductor radius R_0 was 18 mm. The radius of the inner conductor R_I was varied from 0.75 mm to 3.0 mm. Figure 3.4(b) & 3.4(c) show the coaxial cylinder electrode geometry used for the experiments.

The electrodes used were made of brass. They were polished, buffed and cleaned with benzene and ethanol. While handling the electrodes, extreme care was taken not to cause scratches and keep the electrodes free from dust and other impurities.

3.3.2 *Treatment of cryogenic vessel*

Initially, the cryostat vessel used for the above experiments was cleaned with LN_2. After a thorough cleaning, the cryostat was filled with LN_2 of 99.9% purity until the electrode assembly was completely submerged in LN_2. Measurements were made only after bubbling in the LN_2 completely stopped and the temperature of the LN_2 in the cryostat stabilized at 90 K.

Two sets of coaxial cylinders identical in all respects, one for studying the ac breakdown voltages and the other for monitoring the temperature, were mounted horizontally in the cryostat vessel.

3.3.3 *Voltage source & measurement accuracy:*

Same as described in Section 3.1.2

3.3.4 *Temperature measurement & measurement accuracy:*

Same as described in Section 3.1.4

Measurements were made when the temperature of the liquid nitrogen in the cryostat stabilized to 83°K and the temperature of air in the coaxial cylinder provided with temperature probe stabilized to 96°K

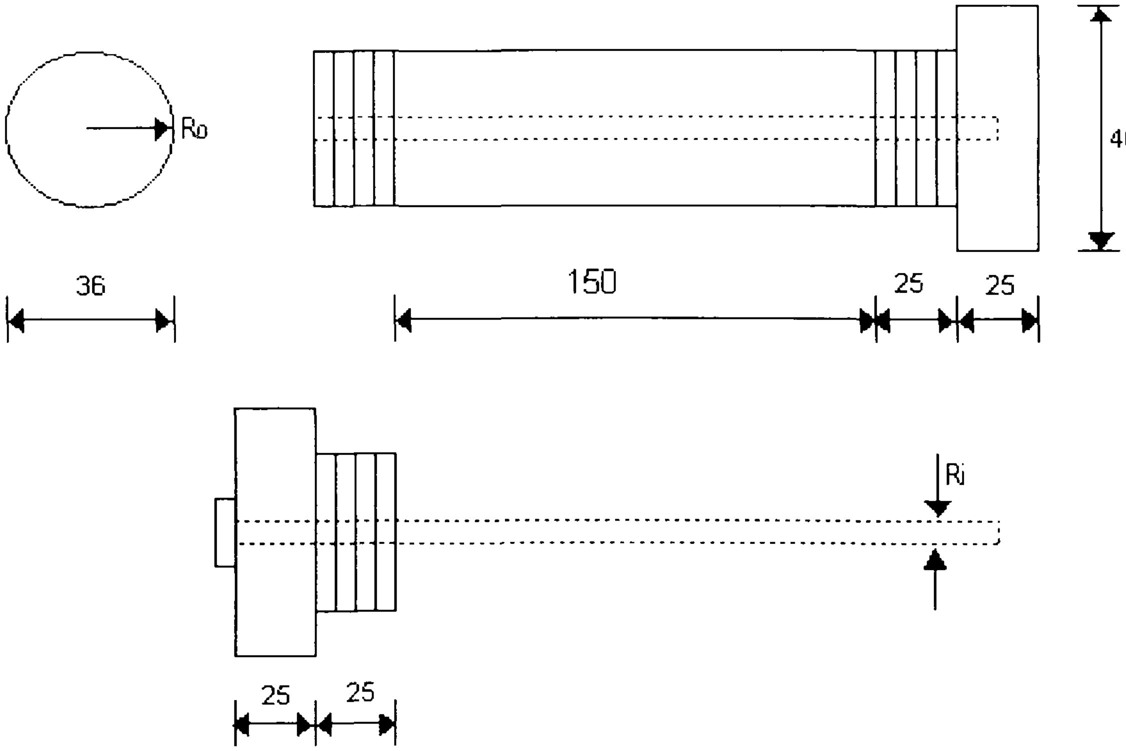


Figure 3.4(a) Coaxial Cylinder Geometry.

(All dimensions are in mm.)

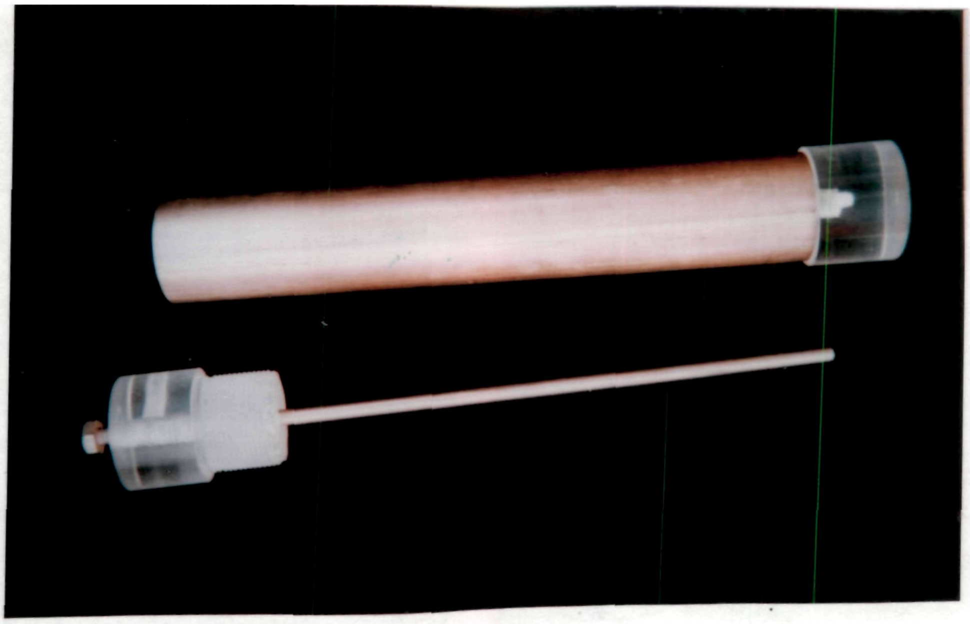


Figure 3.4(b)

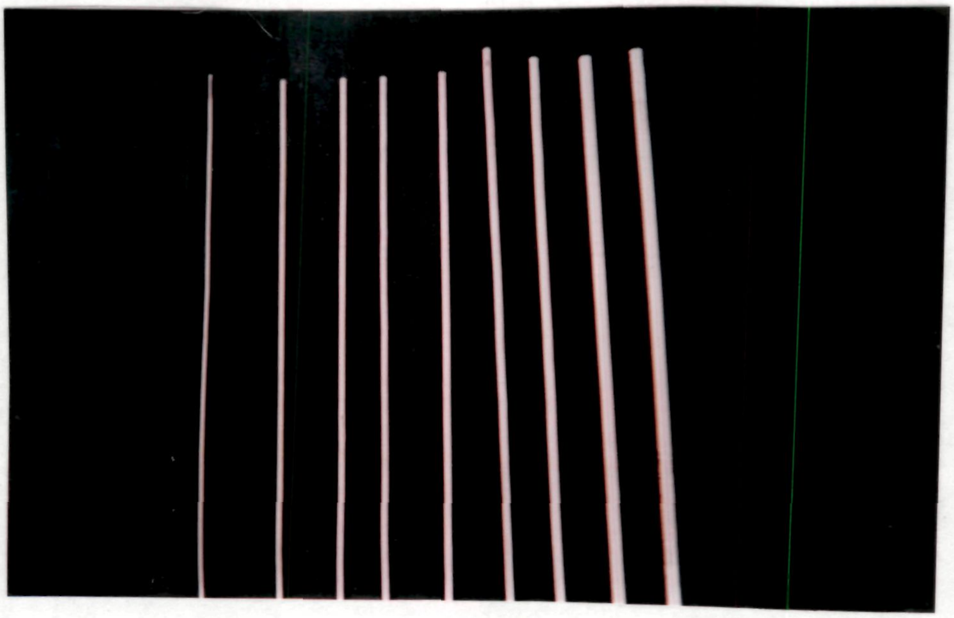


Figure 3.4(c)

LOSS INDEX OF SOLID DIELECTRICS IMMERSED IN LN_2

3.4 Measurement of loss index of solid dielectrics dipped in LN_2:

The importance of ξ_r tan δ (loss index) needs serious consideration at designers end so a study of this parameter in particular is necessary. To measure ξ_r tan δ three-electrode system was used for the measurement of loss index of various dielectrics under liquid nitrogen environment and at atmospheric temperature conditions. The dielectric samples were either cellulosic materials like paper or pressboard or impervious non-cellulosic materials like Perspex. Further the cellulosic materials chosen were of different material densities and treated as per requirement.

3.4.1 *Electrode preparation:*

Figure 3.5(a) & (b) shows the three-electrode system as described in [116] to measure loss index of various dielectrics. Such an arrangement gives rise to a uniform electric field in the measuring gap and ensures that the measured loss is true. The electrode surfaces were made of brass and were polished, buffed and cleaned with benzene and ethanol. While handling care was taken to keep the electrode surfaces untouched and free from scratches, dust and other impurities. The electrodes were mounted vertically in a cryostat vessel and were cleaned and dried before each set of measurements.

3.4.2 *Treatment of the cryostat vessel:*

The same treatment was given as described in Section 3.1.3

3.4.3 *Temperature measurement & measurement accuracy:*

Same as described in Section 3.1.4.

3.4.4 *Measurement of loss index:*

The capacitance, dissipation factor and the resistance of the dielectrics were measured using a LCR data bridge (Forbes Tinsley Company Limited) with an accuracy of ±0.1%. The bridge has built in capability of eliminating the effects of stray capacitances.

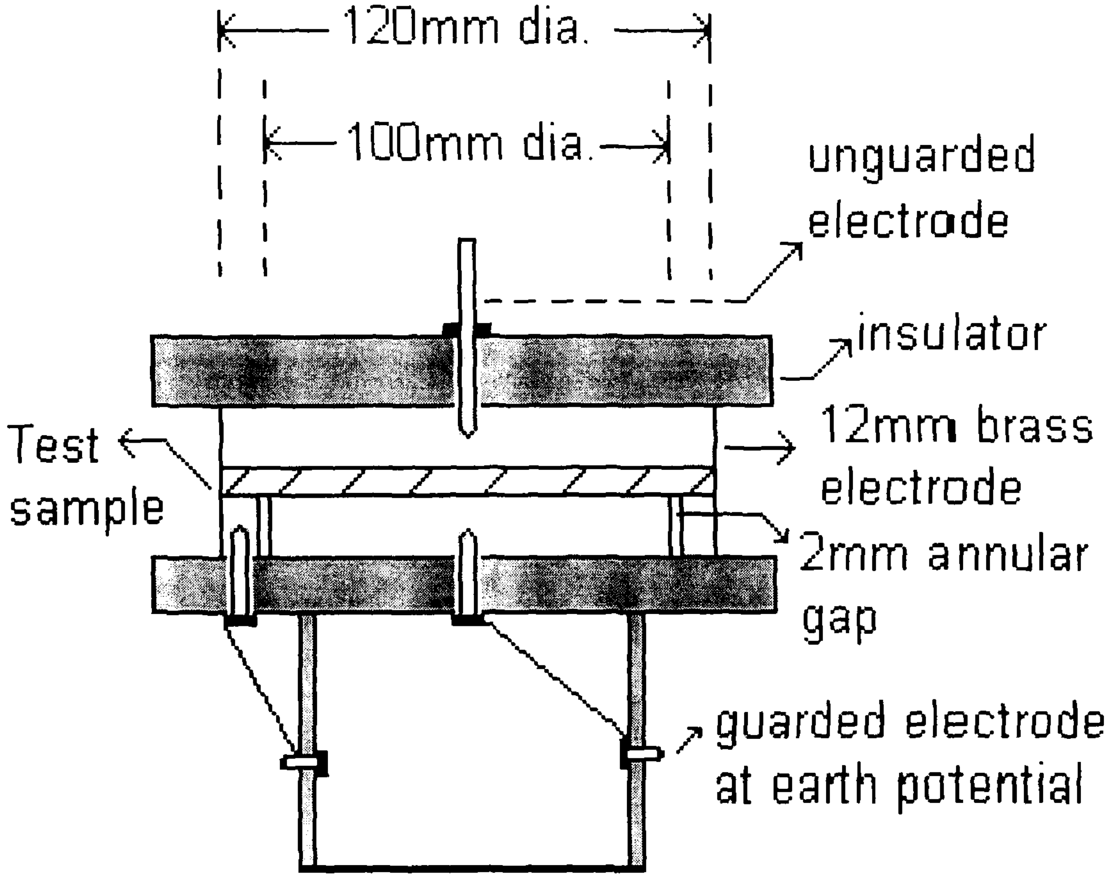

120mm dia.
100mm dia.
unguarded electrode
insulator
Test sample
12mm brass electrode
2mm annular gap
guarded electrode at earth potential

Figure 3.5(a)

Figure 3.5(b)

AREA AND VOLUME EFFECTS ON THE BREAKDOWN STRENGTH OF LN_2

Since the breakdown strength in SF_6 and transformer oil have been reported to decrease with increasing electrode surface area or volume subjected to high electric stress it became imperative to attempt such a study and compare the results existing in the literature [34]. The area and volume effect of LN_2 has been studied using two sets of electrode system; namely Sphere-plane and coaxial cylinders as shown in Figures 3.7 & 3.8(a) respectively.

3.5 Breakdown Voltage measurement with Sphere to Plane electrode

3.5.1 *Electrode preparation*:

Figure 3.6(a) & (b) shows the various electrode geometries used for the breakdown voltage measurements in liquid nitrogen. The HV electrode material and shapes & sizes are given in Table 3.1. The table also shows the different gap lengths of electrodes used. A plane electrode of 90 mm in diameter made of brass was used as the ground electrode. The electrodes were polished, buffed and cleaned with benzene and ethanol. While handling care was taken to keep the electrode surfaces untouched and free from scratches, dust and other impurities. The electrodes were mounted horizontally in a cryostat vessel. A number of observations were noted in succession without checking the surface condition of electrodes and the average of about seven observations with standard deviation of ±2.3 is reported.

3.5.2 *Treatment of the cryostat vessel:*

Figure 3.7 shows the cryostat vessel used for the above experiments. Initially, the cryostat vessel used for the above experiments was cleaned with LN_2. After a thorough cleaning, the cryostat was filled with LN_2 until the electrode assembly was completely filled. The axis of sphere to plane electrodes was placed horizontally and immersed in liquid nitrogen. Measurements were initiated only after bubbling in the LN_2 completely stopped and the temperature of the liquid in the cryostat stabilized. Ground electrode was kept fixed and sliding the HV electrode with the help of micrometer varied the gap length.

3.5.3 *Temperature measurement & measurement accuracy:*

Same as described in Section 3.1.4

3.5.4 *Voltage source & measurement accuracy:*

Same as described in Section 3.1.2. The applied voltage was raised at a uniform rate of 5 kV/s.

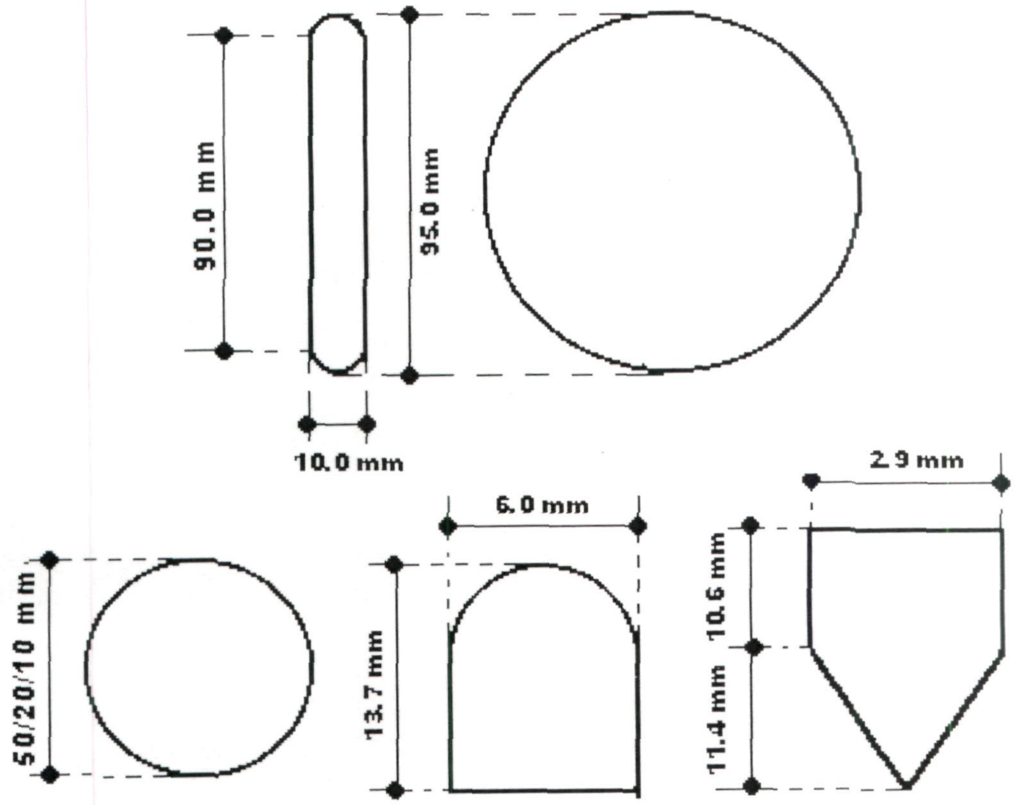


Figure 3.6(a) Shapes and Sizes of Electrodes used (All Dimensions in mm)

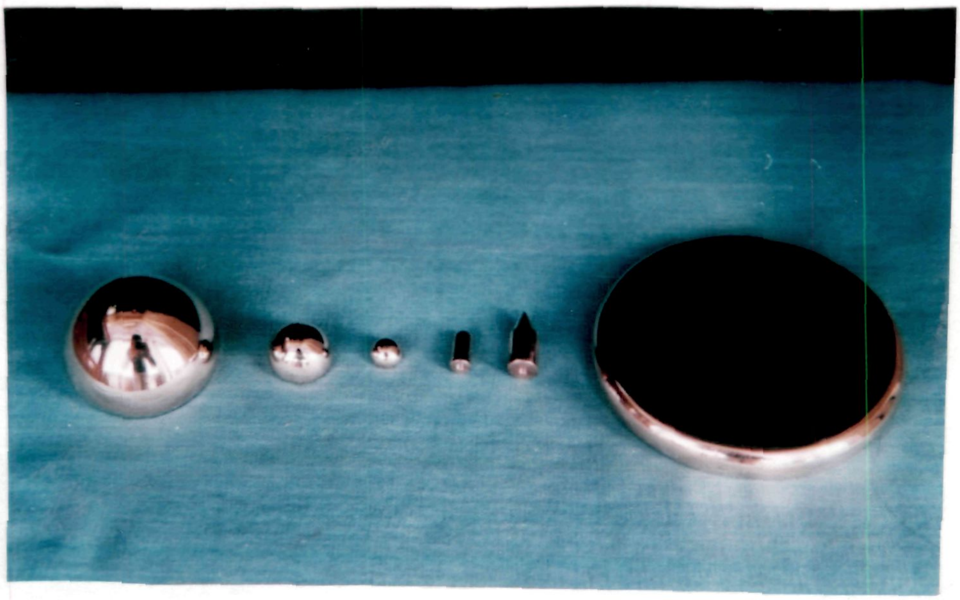


Figure 3.6(b)

Diameter	50	20	10	6	1
Shape	Sphere			Rod	Needle
Gap	0.5,1.0,1.5				
Material	Brass				

Table3.1 HV Electrodes used for Breakdown Measurements (Unit: mm)

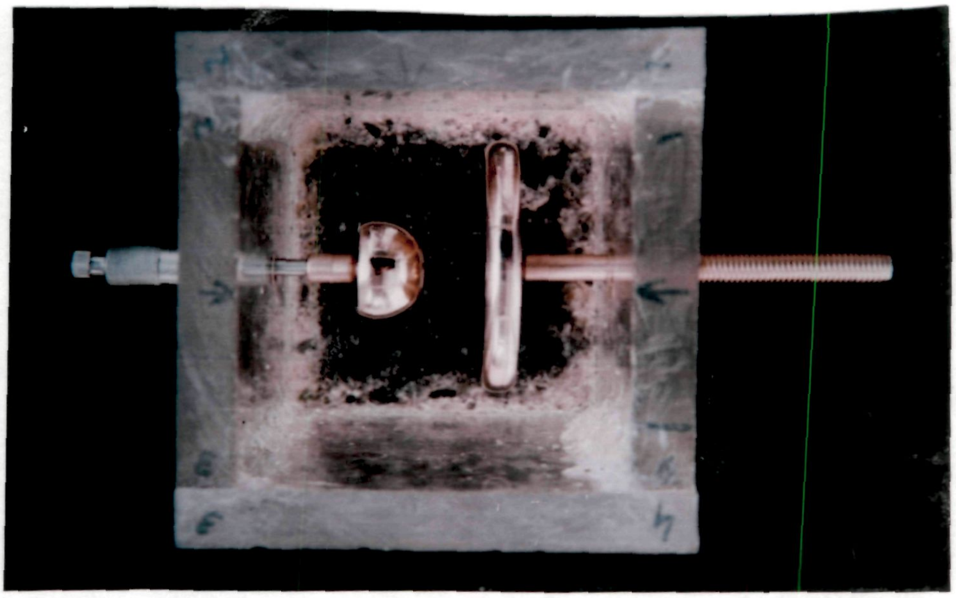


Figure 3.7 Cryogenic Vessel Used

3.6 Breakdown Voltage measurements with coaxial cylindrical electrode

3.6.1 *Electrode preparation:*

Figure 3.8(a) & (b) shows the coaxial cylindrical electrode geometry used for breakdown voltage measurements. Table3.2 shows the dimensions of test coaxial cylindrical electrodes used for breakdown voltage measurements.

The tested gap lengths were set at 3.0, 4.5 and 6.0 mm for the three lengths of HV electrodes viz. 30, 100 and 350 mm. All electrodes were made of brass. The axes of coaxial electrodes were placed vertically and arrangement was applied in thermocol box filled with liquid nitrogen. Outer cylindrical electrode was grounded and 50 Hz ac voltage was applied to inner cylindrical electrode.

3.6.2 *Temperature measurement & measurement accuracy:*

Same as described in Section 3.1.4

3.6.3 *Voltage source & measurement accuracy:*

Same as described in Section 3.1.2. The applied voltage was raised at a uniform rate of 5 kV/s.

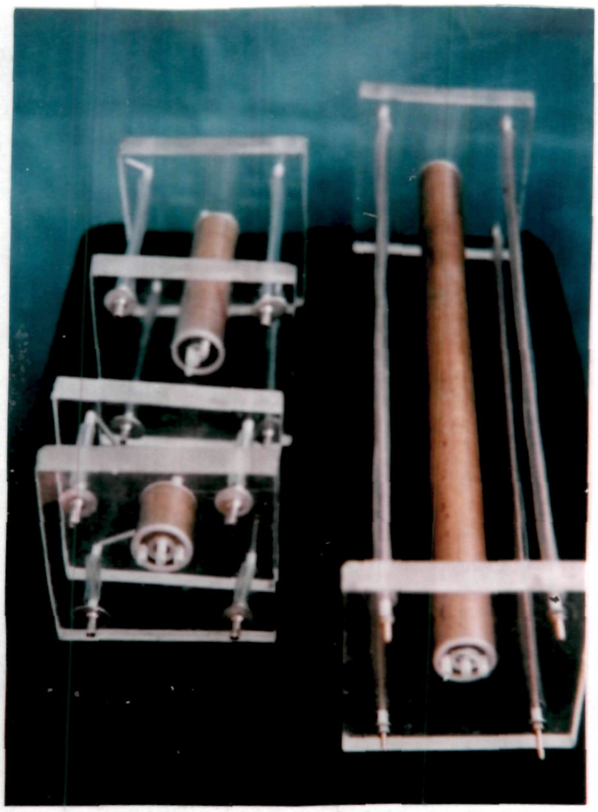


Figure 3.8 (a)

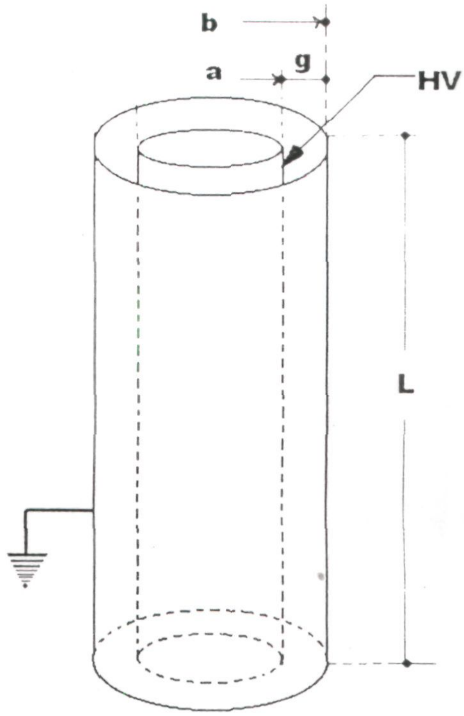


Figure 3.8 (b)

Figure 3.8. Coaxial Cylindrical Electrode Geometry

a (Inner Cylinder radius)	16,13,10
b (Outer Cylinder radius)	22
g (Gap Length)	3.0,4.5,6.0
L (Effective Electrode Length)	30,100,350

Table3.2 Dimensions of Test Coaxial Cylindrical Electrodes used for Breakdown Measurement (Unit: mm)

CHAPTER-4

RESULTS

4.1 AC BREAKDOWN VOLTAGE IN LN_2

OBSERVATIONS

Gap length (mm)	I		II		Mean BD Voltage	BD Strength
	LV (Volts)	HV (KV)	LV (Volts)	HV (KV)	(K V)	(KV/mm)
5	134	80	140	85	82.5	16.5
4	122	74	122	74	74.0	18.5
3	90	55	98	59	57.0	19.0
2	66	40	66	40	40.0	20.0
1	30	18	30	18	18.0	18.0

Table 4.01.Sphere-Sphere

Gap length (mm)	I		II		Mean BD Voltage	BD Strength
	LV (Volts)	HV (KV)	LV (Volts)	HV (KV)	(K V)	(KV/mm)
5	140	85	150	90	87.5	17.5
4	124	75	124	75	75.0	18.75
3	100	60	110	67	63.5	21.17
2	70	45	80	49	46.0	23.0
1	52	32	44	26	29.0	29.0

Table 4.02.Plane-Plane

Gap length (mm)	I		II		Mean BD Voltage	BD Strength
	LV (Volts)	HV (KV)	LV (Volts)	HV (KV)	(K V)	(KV/mm)
5	130	78	120	73	75.5	15.10
4	110	67	110	67	67.0	16.75
3	70	43	72	45	44.0	14.67
2	60	36	52	32	34.0	17.00
1	20	13	24	15	14.0	14.00

Table 4.03.Hemisphere- Hemisphere

Gap length (mm)	I		II		Mean BD Voltage	BD Strength
	LV (Volts)	HV (KV)	LV (Volts)	HV (KV)	(K V)	(KV/mm)
5	80	49	78	47	48	09.60
4	70	43	64	39	41	10.25
3	58	35	54	33	34	11.33
2	52	32	52	32	32	16.00
1	30	18	32	20	19	19.00

Table 4.04.Cone-Cone

Gap length (mm)	I		II		Mean BD Voltage	BD Strength
	LV (Volts)	HV (KV)	LV (Volts)	HV (KV)	(K V)	(KV/mm)
5	124	75	120	73	74	14.80
4	104	63	110	67	65	16.25
3	80	49	84	51	50	16.67
2	60	36	68	42	38	19.00
1	24	15	20	13	14	14.00

Table 4.05.Sphere-Plane

Gap length (mm)	I		II		Mean BD Voltage	BD Strength
	LV (Volts)	HV (KV)	LV (Volts)	HV (KV)	(K V)	(KV/mm)
5	116	70	110	67	68.5	13.0
4	98	59	92	57	58.0	14.5
3	84	51	84	51	51.0	17.0
2	60	36	56	34	35.0	17.5

Table 4.06.Sphere-Hemisphere

Gap length (mm)	I		II		Mean BD Voltage	BD Strength
	LV (Volts)	HV (KV)	LV (Volts)	HV (KV)	(K V)	(KV/mm)
5	100	60	98	59	59.5	11.9
4	90	55	86	52	53.5	13.4
3	84	51	84	51	51.0	17.0
2	44	26	56	32	29.0	14.5
1	14	8	14	8	08.0	08.0

Table 4.07.Cone -Sphere

Gap length (mm)	I		II		Mean BD Voltage	BD Strength
	LV (Volts)	HV (KV)	LV (Volts)	HV (KV)	(K V)	(KV/mm)
5	100	60	104	63	61.5	12.30
4	94	57	90	55	56.0	14.00
3	80	49	64	39	44.0	14.67
2	50	30	54	32	31.0	15.50
1	16	10	16	10	10.0	10.00

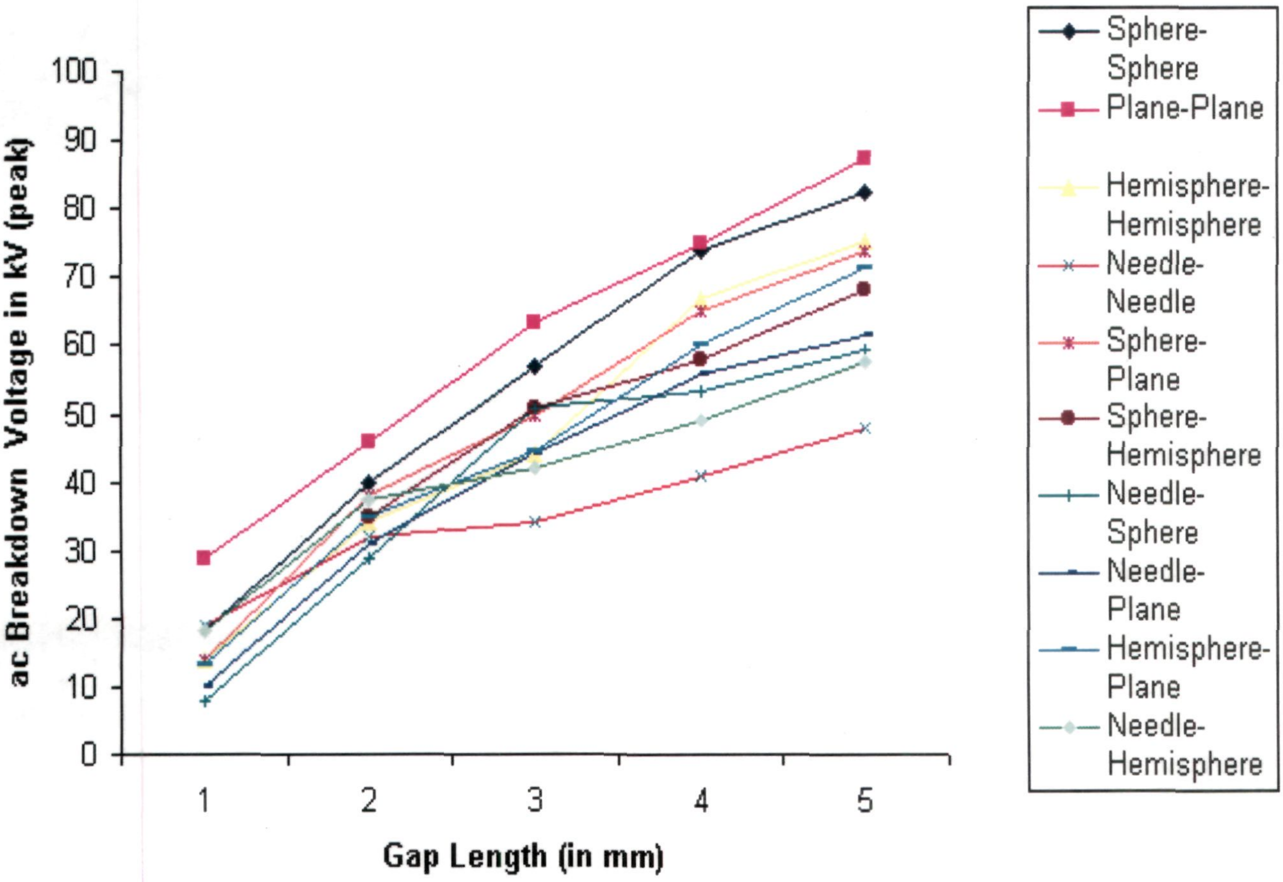
Table 4.08.Cone-Plane

Gap length (mm)	I		II		Mean BD Voltage	BD Strength
	LV (Volts)	HV (KV)	LV (Volts)	HV (KV)	(K V)	(KV/mm)
5	120	73	116	70	71.5	14.30
4	100	60	100	60	60.0	15.00
3	70	43	76	46	44.5	14.83
2	60	36	56	34	35.0	17.50
1	20	13	20	13	13.0	13.00

Table 4.09.Hemisphere-Plane

Gap length (mm)	I		II		Mean BD Voltage	BD Strength
	LV (Volts)	HV (KV)	LV (Volts)	HV (KV)	(K V)	(KV/mm)
5	100	60	90	55	57.5	11.50
4	80	49	80	49	49.0	12.25
3	64	39	72	45	42.0	14.00
2	60	36	64	39	37.5	18.75
1	30	18	30	18	18.0	18.00

Table 4.10.Cone-Hemisphere



100
90
80
70
60
50
40
30
20
10
0
ac Breakdown Voltage in kV (peak)
1
2
3
4
5
Gap Length (in mm)
Sphere-Sphere
Plane-Plane
Hemisphere-Hemisphere
Needle-Needle
Sphere-Plane
Sphere-Hemisphere
Needle-Sphere
Needle-Plane
Hemisphere-Plane
Needle-Hemisphere

Figure 4.01

Tables 4.01-4.10 shows the observations made for ac breakdown voltage in LN_2 with gap length for different electrode configurations.

Figure 4.01 shows the variation of the ac breakdown voltage in LN_2 with gap length for different electrode configurations. Each point on the curve represents an average of 20 breakdown measurements. For clarity, the deviations in measurements are not shown in the figure but for most of the measurements the standard deviation was ±2.4kV.However for the cone-cone electrode geometry, the standard deviation was found to be ±3.7 kV.

4.2 BREAKDOWN STRENGTH OF SOLID DIELECTRICS DIPPED IN LN_2

Breakdown Strength of Solid Dielectrics Immersed in LN_2 :

The breakdown strength of solid dielectrics measured at room temperature (27^0C to 29^0C) and when dipped in LN_2 are given in Table 4.11. The reported breakdown strength is the average value of 20 measurements with a standard deviation of ±2.7.

Sample Number	Insulating material	Breakdown strength at room temp. (KV/mm)	Breakdown strength at cryogenic temp. (KV/mm)
1	Cotton tape	4	30
2	Empire tape	7	44
3	Kraft paper	15	45
4	Polyester film	58	95
5	Leatheroid	19	100
6	Tyvek	47	53
7	Varnished paper	9	49
8	Bakelite	15	47
9	Mica sheet	36	88
10	Minimax	79	88
11	PVC tape	54	88
12	Perspex	23	36
13	Cable PVC	10	28

TABLE 4.11

The results are illustrated by means of a bar chart in Figure 4.02

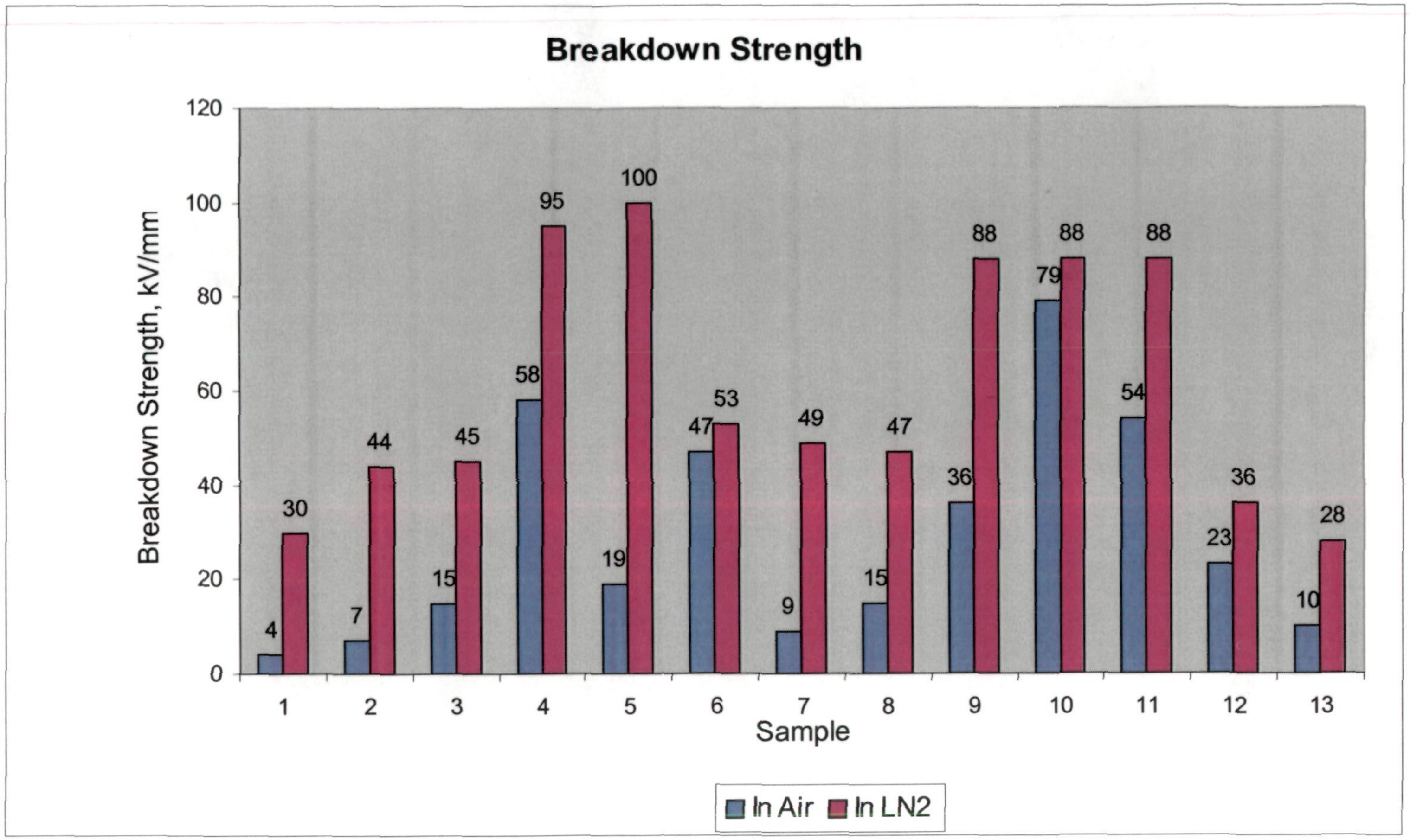


Figure 4.02: AC breakdown strength of various solid dielectrics in air and in LN_2 using 12.5 mm spherica

4.3 BREAKDOWN OF CRYOGENIC AIR UNDER NON-UNIFORM FIELDS

Breakdown of cryogenic Air under Non-Uniform Fields

Table 4.12 shows the ac breakdown voltages in air at room temperature and cryogenic temperature observed in the laboratory using coaxial geometry for different gap lengths (R_0- R_I) between inner and outer conductors. Each observation represents an average of 10 breakdown voltages. For clarity, the deviations in measurements are not shown, but for most of the measurements the standard deviation was ± 2.2 kV.

S.No.	Gap (mm) $G=(R_o - R_i)$	Breakdown voltage (kV) <u>Air at room temperature</u>	Breakdown voltage (kV) <u>Air at cryogenic temperature</u>
1.	17.25	10.1	12.03
2.	17.1	11.5	13.20
3.	16.85	14.1	15.66
4.	16.68	14.2	15.80
5.	16.52	14.9	16.85
6.	16.37	15.1	17.03
7.	16.2	15.6	17.78
8.	16.0	16.1	18.50
9.	15.25	18.6	21.92
10.	15.0	19.1	22.43

Table 4.12 AC Breakdown voltages in air at room temperature and at cryogenic temperature.

(Ro= 18mm and R_i = 0.75, 0.9, 1.15, 1.32, 1.475, 1.625, 1.8, 2.0, 2.75 and 3.0 mm)

S.No.	GAP (mm) $G=R_0-R_i$	RITZ Uniform Field BDV (kV)	Toyota Sp.to Sp. BDV (kV)	$U^{0.85}$	$BDV_{co\text{-}axial}$ (kV)		
					RITZ[5] RITZ* $U^{0.85}$	Toyota [2] Toyota * $U^{0.85}$	Observed in the laboratory
1.	17.25	51.17	50.570	0.186	09.52	09.60	10.1
2.	17.10	50.76	50.170	0.208	10.56	10.54	11.5
3.	16.85	50.49	49.495	0.242	12.01	11.88	14.1
4.	16.68	49.61	49.036	0.262	13.00	12.75	14.2
5.	16.52	49.10	48.604	0.279	13.72	13.61	14.9
6.	16.37	48.78	49.199	0.296	14.44	13.98	15.1
7.	16.20	48.30	47.740	0.314	15.17	14.80	15.6
8.	16.00	47.75	47.200	0.334	15.95	15.58	16.1
9.	15.25	45.71	45.175	0.399	18.24	18.10	18.6
10.	15.00	45.03	44.500	0.418	18.82	18.69	19.1

Table 4.13 Breakdown voltages (Ritz uniform fields, Toyota sphere to sphere, Ritz and Toyota's non-uniform and observed values in the laboratory) in air at room temperature.

S.No.	GAP (mm) $g=R_o-R_i$	Toyota Sp.to Sp. BDV (kV)	$U^{0.85}$	$BDV_{coaxial}$ (kV)	
				Toyota	Observed in the laboratory
1.	17.25	58.13	0.186	11.04	12.03
2.	17.10	57.75	0.208	12.13	13.20
3.	16.85	57.13	0.242	13.71	15.66
4.	16.68	56.70	0.262	14.74	15.80
5.	16.52	56.30	0.279	15.76	16.85
6.	16.37	55.93	0.296	16.22	17.03
7.	16.20	55.50	0.314	17.21	17.78
8.	16.00	55.00	0.334	18.15	18.50
9.	16.25	53.13	0.399	21.25	21.92
10.	15.00	52.50	0.418	22.05	22.43

Table 4.14 Breakdown voltages (Toyota's sphere to sphere, Toyota's non-uniform and observed values in the laboratory, in air at cryogenic temperature).

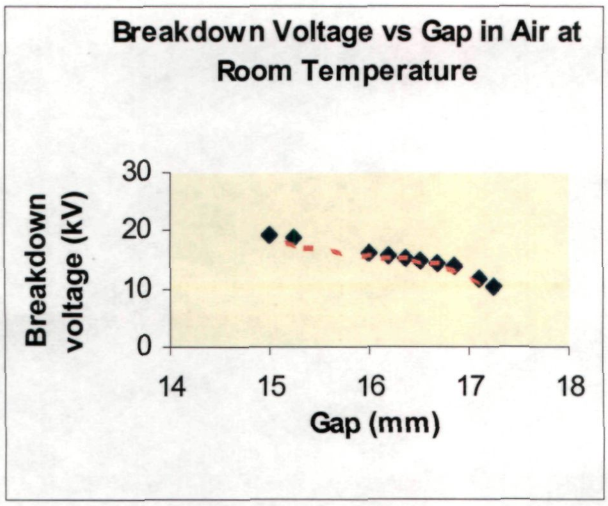


Figure 4.03 Breakdown Voltage vs. Gap in air at room temperature.

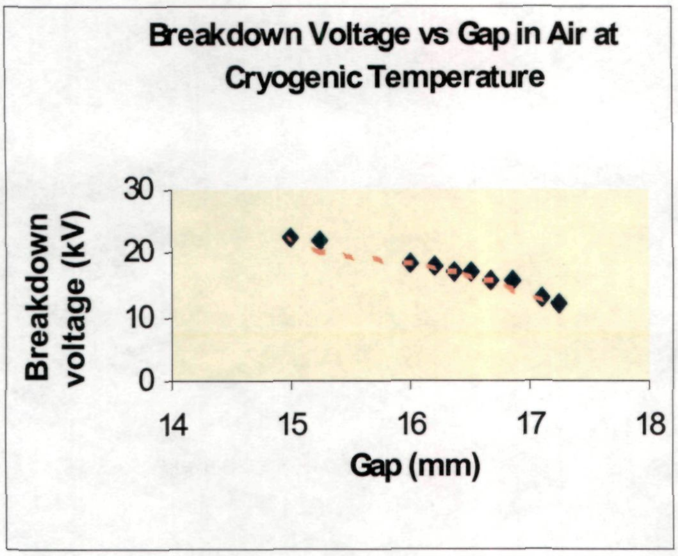


Figure 4.04 Breakdown Voltage vs. Gap in air at cryogenic temperature.

4.4 LOSS INDEX OF SOLID DIELECTRICS IMMERSED IN LN_2

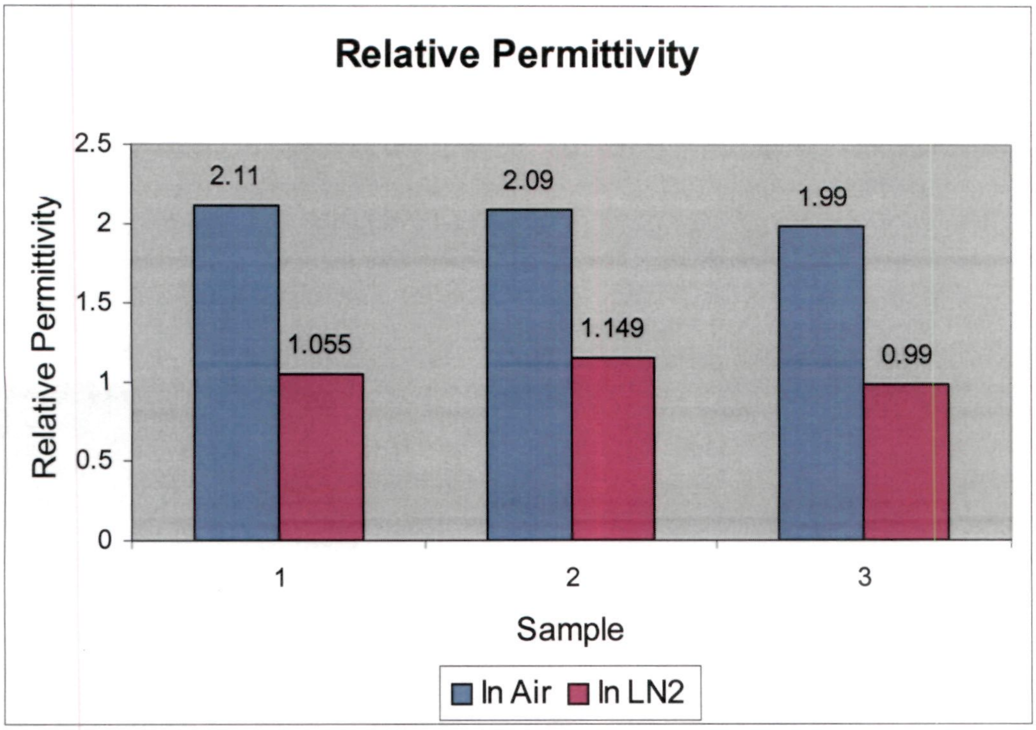
Loss Index of solid Dielectrics immersed in liquid nitrogen

Figures 4.05 to 4.13 illustrate the measured relative permittivity and loss index of various dielectrics immersed in liquid nitrogen. These values are compared with the relative permittivity and loss indices for the same set of dielectrics at room temperature.

Each bar chart is a representation of the average values of 10 samples of each dielectric tested in liquid nitrogen and in air. The standard deviations in all measurements were ± 0.24 for the relative pemittivity and ±0.09 for the loss index.

Table 4.15 Relative Permittivity and loss index of solid Dielectrics as measured in air & when dipped in liquid nitrogen

Solid Dielectric	Sample No.	In Air			In LN_2		
		ξ_r	$\tan\delta$	$\xi_r\tan\delta$	ξ_r	$\tan\delta$	$\xi_r\tan\delta$
Crepe Paper	I	2.11	0.178	0.375	1.055	0.077	0.081
	II	2.09	0.174	0.3636	1.149	0.077	0.089
	III	1.99	0.145	0.288	0.99	0.062	0.061
Kraft Paper	I	2.11	0.125	0.264	1.06	0.053	0.056
	II	2.234	0.135	0.302	1.03	0.059	0.061
	III	1.563	0.098	0.153	1.03	0.058	0.06
Pressboard-I	I	2.11	0.169	0.358	1.65	0.094	0.155
	II	2.98	0.119	0.354	1.58	0.090	0.142
	III	2.83	0.111	0.314	1.6	0.097	0.155
Pressboard-II	I	2.948	0.089	0.262	1.403	0.072	0.101
	II	3.364	0.117	0.394	1.679	0.049	0.082
Pressboard-III	I	2.948	0.173	0.511	1.58	0.025	0.039
	II	2.299	0.113	0.260	1.172	0.055	0.065
Polythene Coated Paper	I	2.948	0.072	0.2122	2.093	0.064	0.133
	II	3.012	0.065	0.195	2.198	0.059	0.129
Perspex	I	3.43	0.040	0.1372	3.121	0.033	0.1029
	II	3.425	0.047	0.1609	3.048	0.036	0.1097
	III	3.398	0.045	0.1529	2.956	0.038	0.1123
Thermoplastic	I	4.91	0.085	0.4173	4.24	0.078	0.3307
	II	4.92	0.085	0.4182	4.23	0.059	0.249
	III	4.62	0.083	0.3834	4.14	0.072	0.298
Presspahn	I	0.73	0.079	0.058	0.624	0.080	0.05
	II	0.737	0.076	0.056	0.637	0.080	0.051
	III	0.711	0.082	0.058	0.614	0.081	0.05



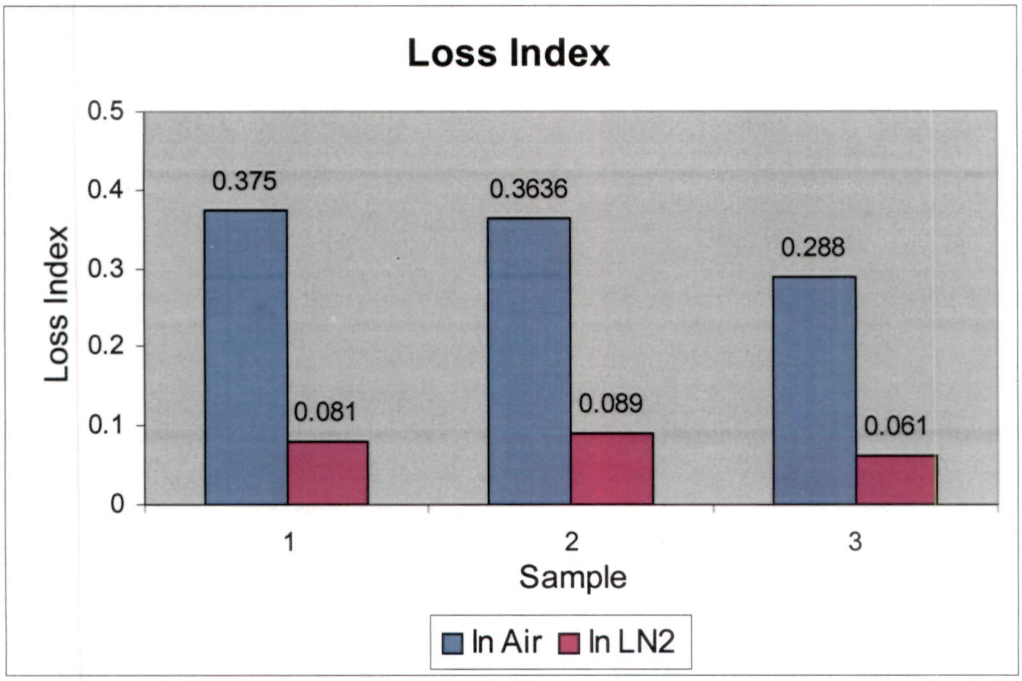
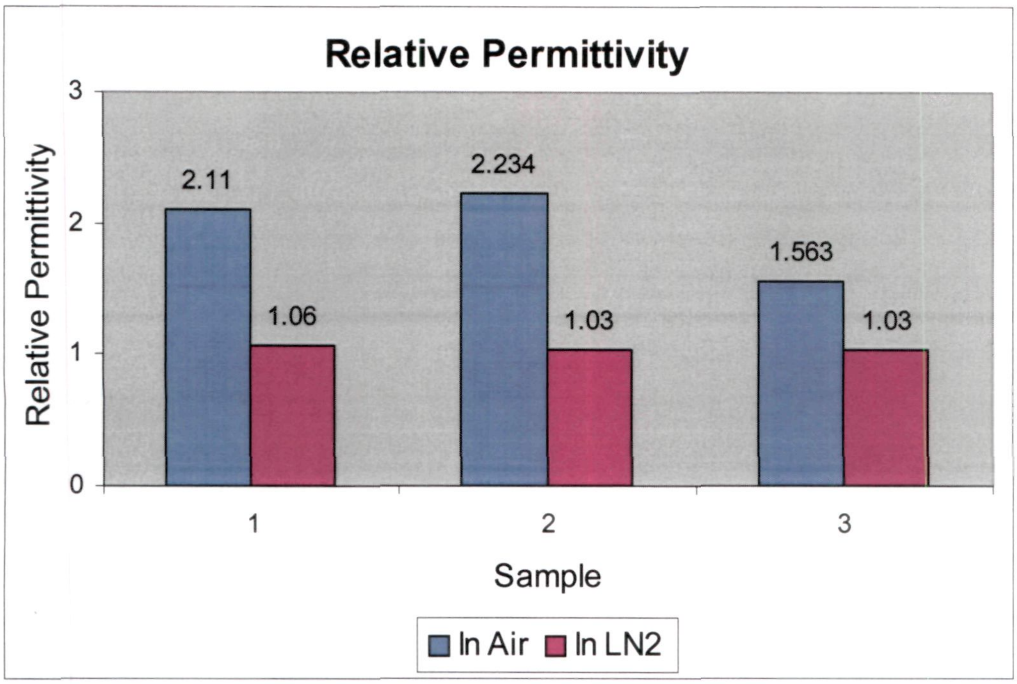


Fig.4.05: Comparison of (a) relative permittivity (b) loss index of **Crepe Paper** (material density 0.9gm/cm^3) in air and in LN_2.



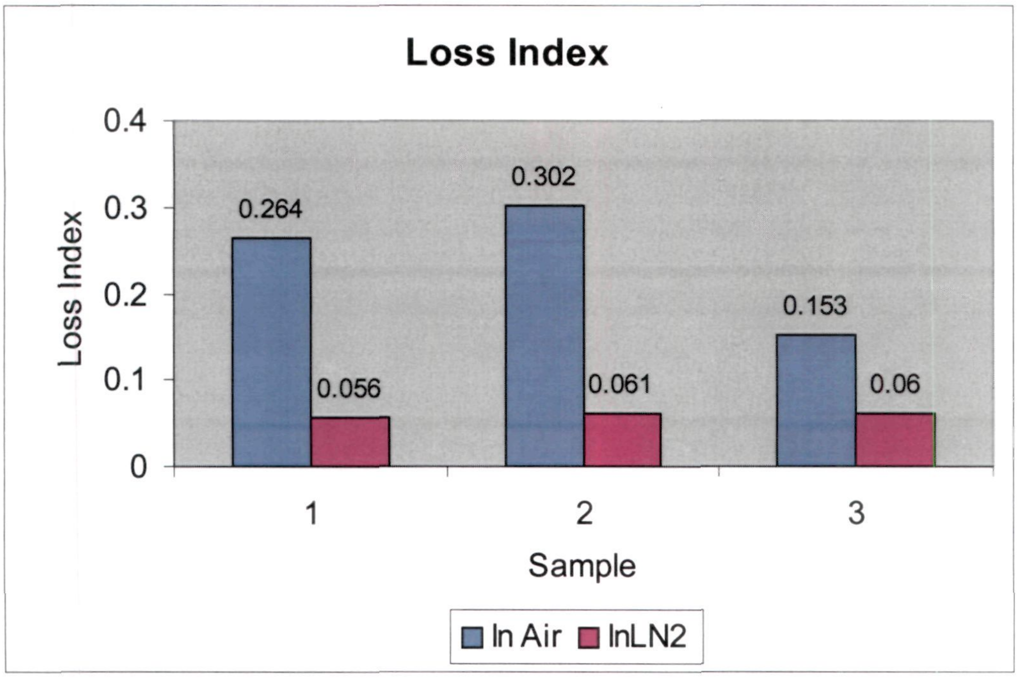
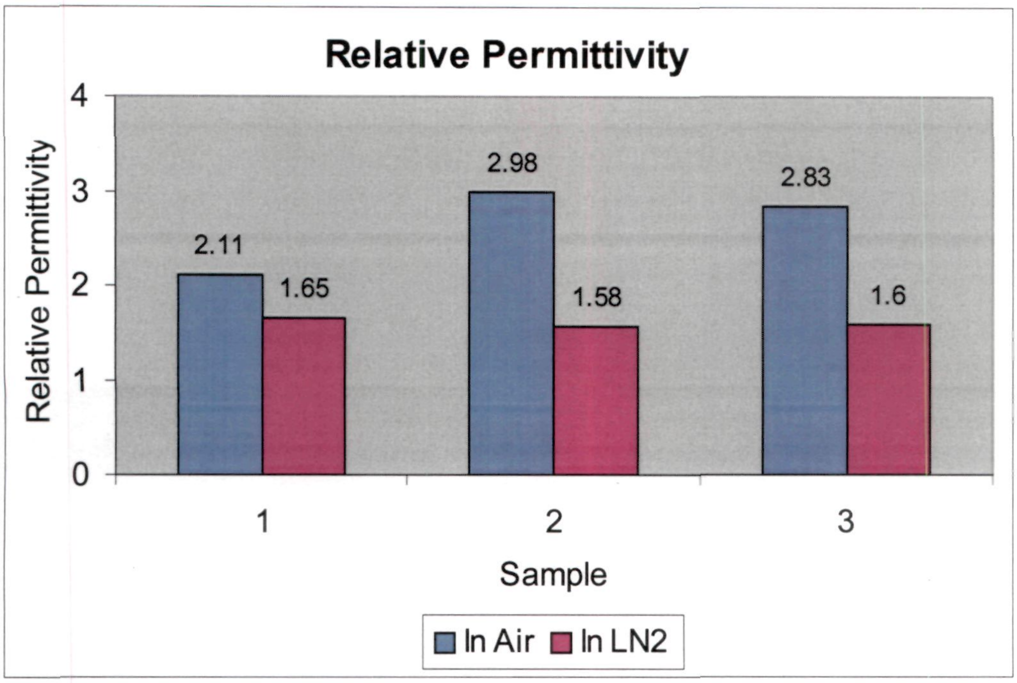


Fig.4.06: Comparison of (a) relative permittivity (b) loss index of **Kraft Paper** (material density 1.01gm/cm^3) in air and in LN_2.



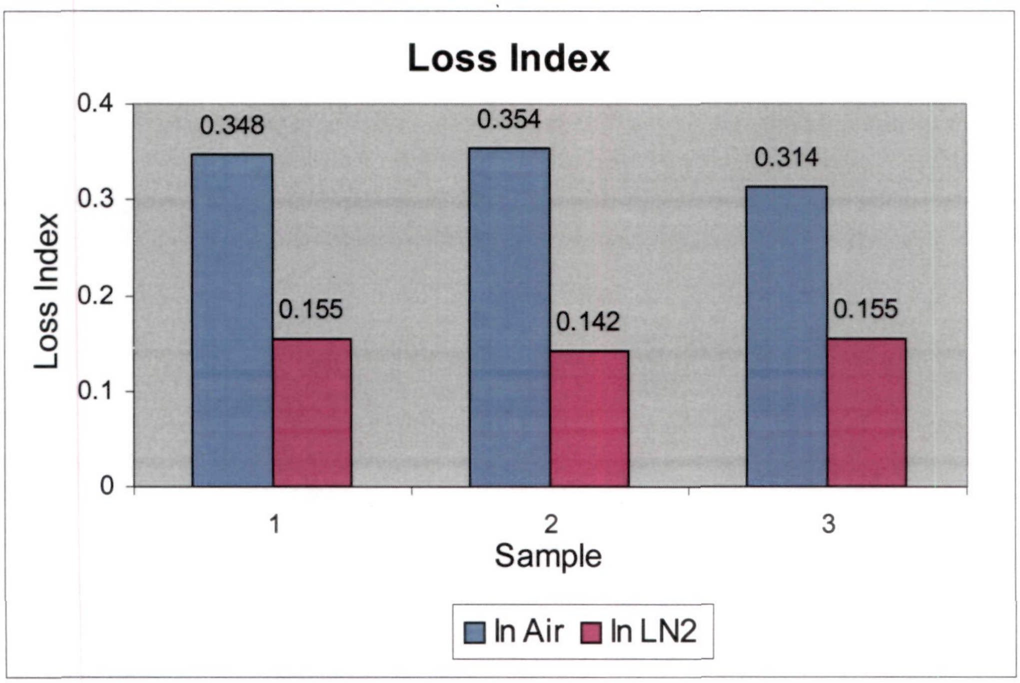
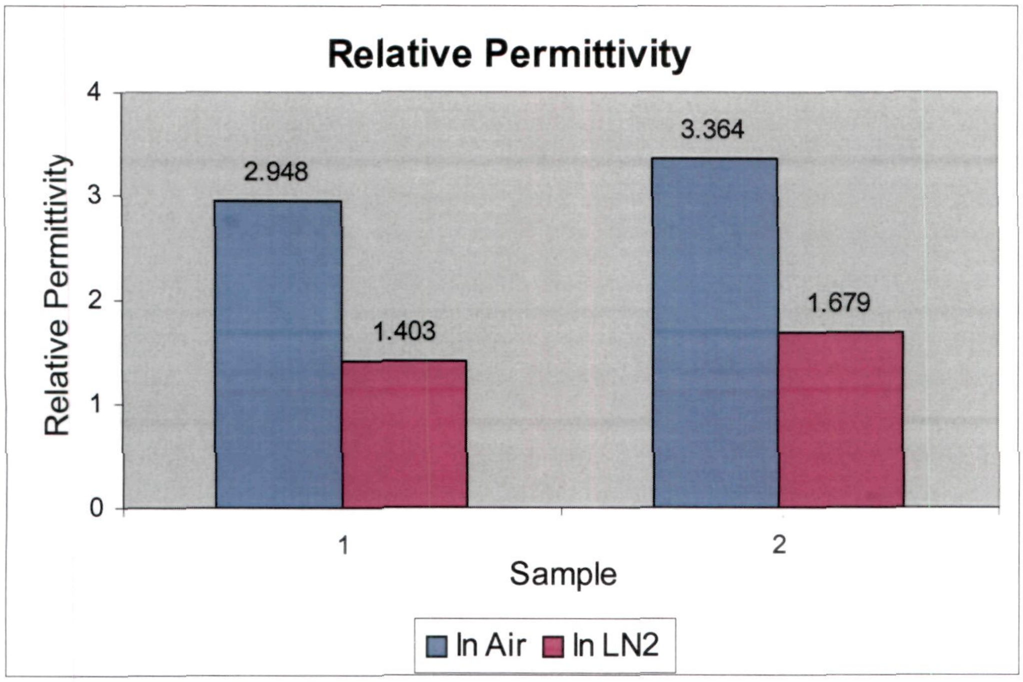


Fig.4.07: Comparison of (a) relative permittivity (b) loss index of **Pressboard-I** (material density 1.28gm/cm^3) in air and in LN_2.



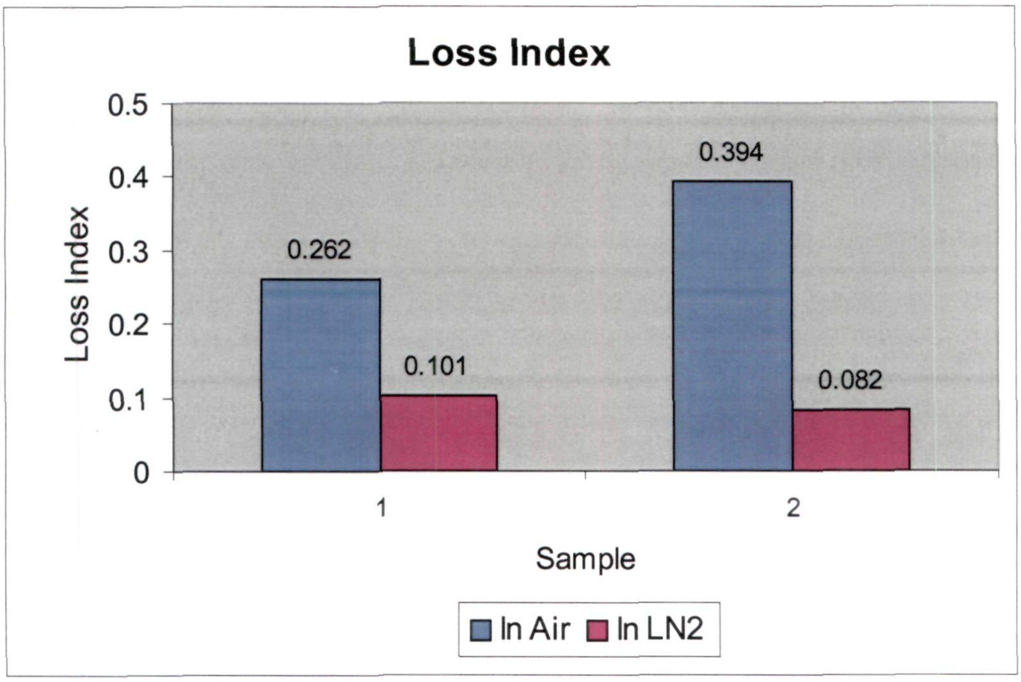
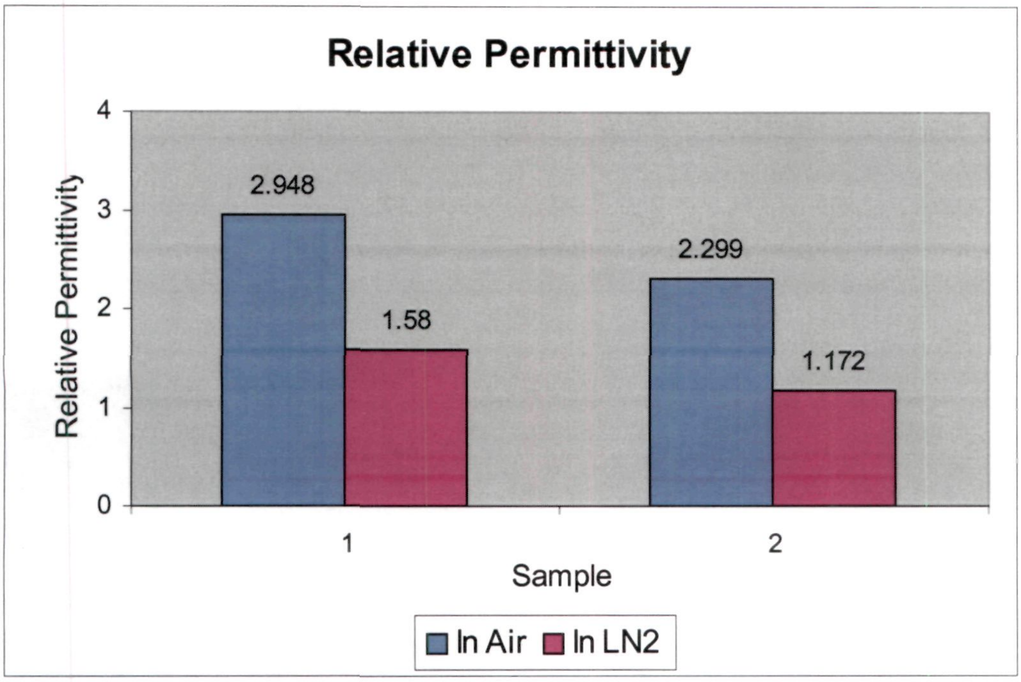


Fig.4.08: Comparison of (a) relative permittivity (b) loss index of **Pressboard-II** (material density 1.15gm/cm^3) in air and in LN_2.



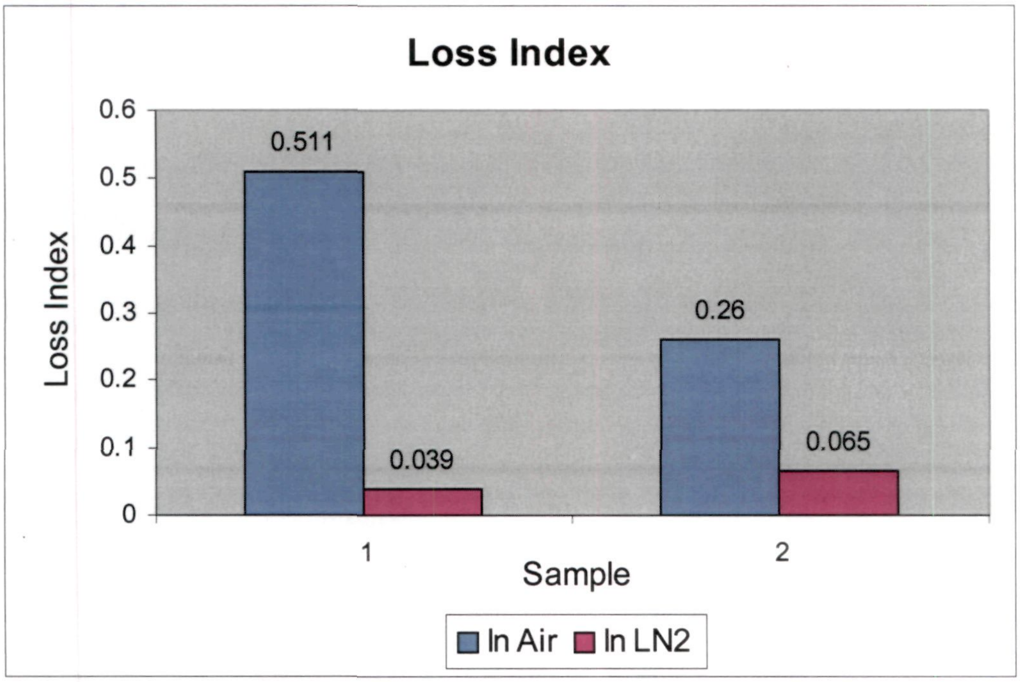


Fig.4.09: Comparison of (a) relative permittivity (b) loss index of **Pressboard-III** (material density 1.04gm/cm^3) in air and in LN_2.

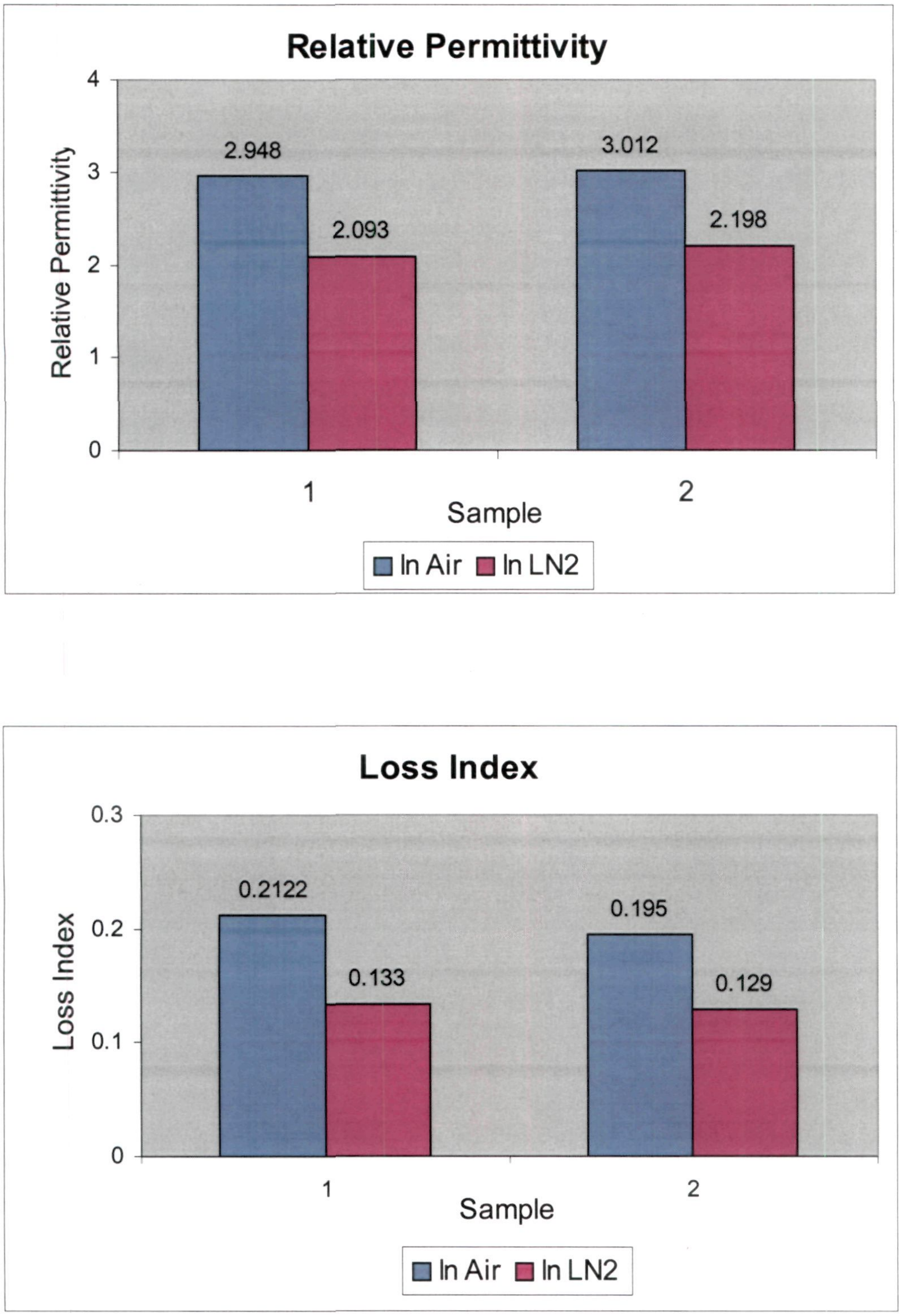
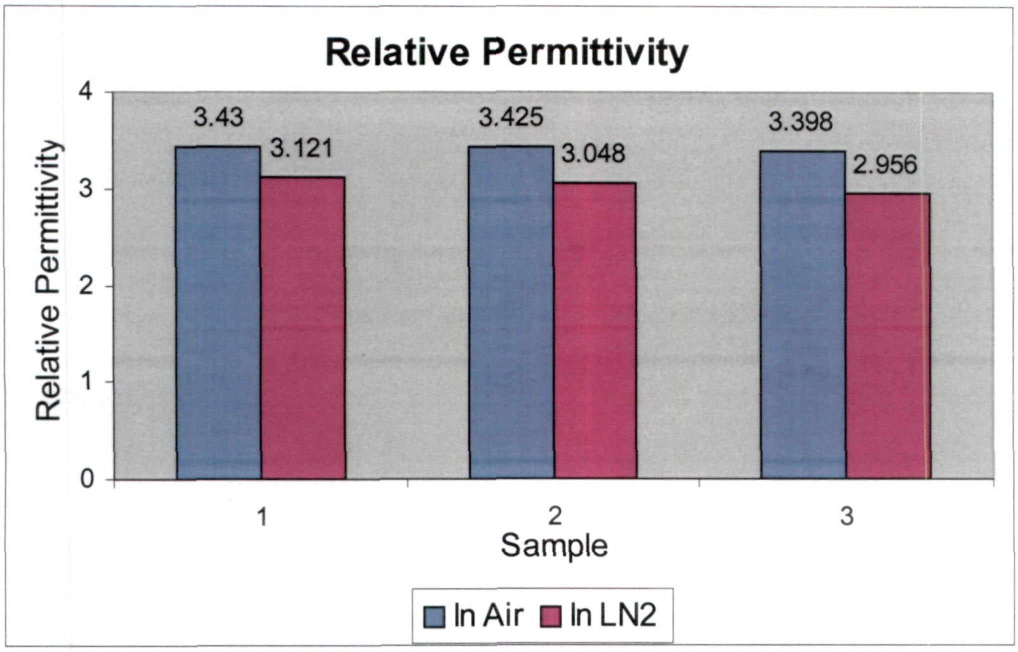


Fig.4.10: Comparison of (a) relative permittivity (b) loss index of **Polythene coated paper** in air and in LN_2.



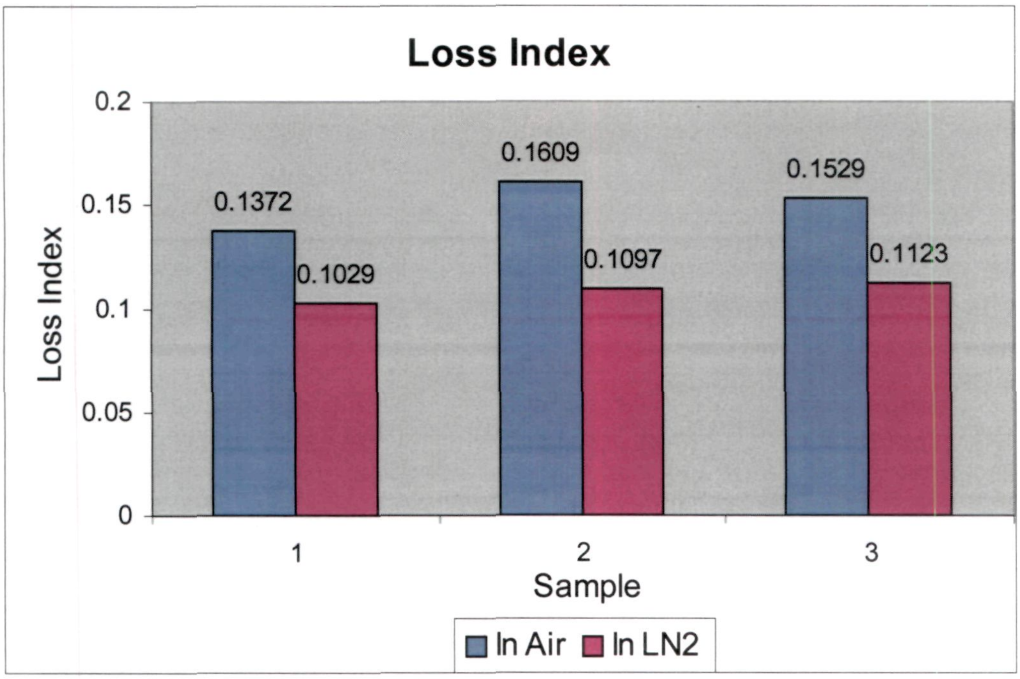
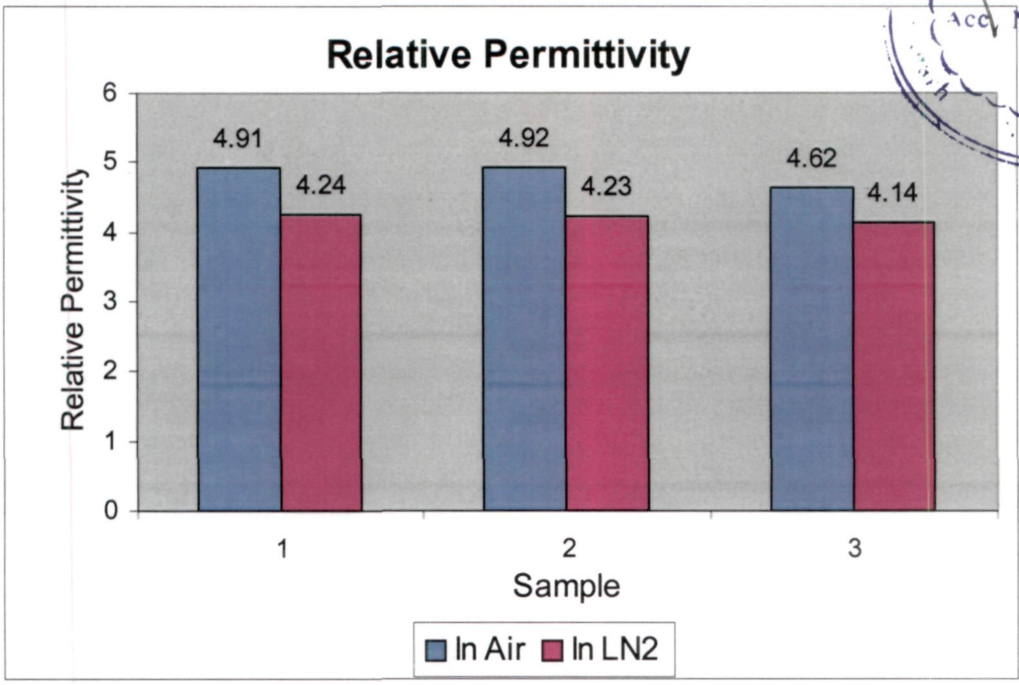


Fig.4.11: Comparison of (a) relative permittivity (b) loss index of **Perspex** in air and in LN_2.



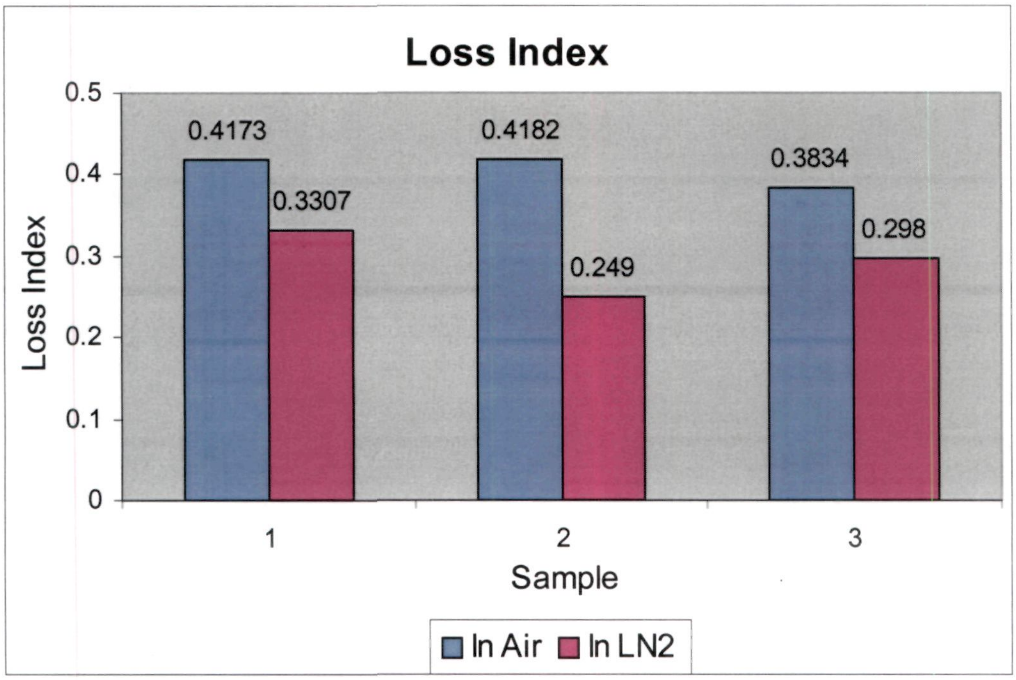


Fig.4.12: Comparison of (a) relative permittivity (b) loss index of **Thermoplastic** (Nylon 6) in air and in LN_2.

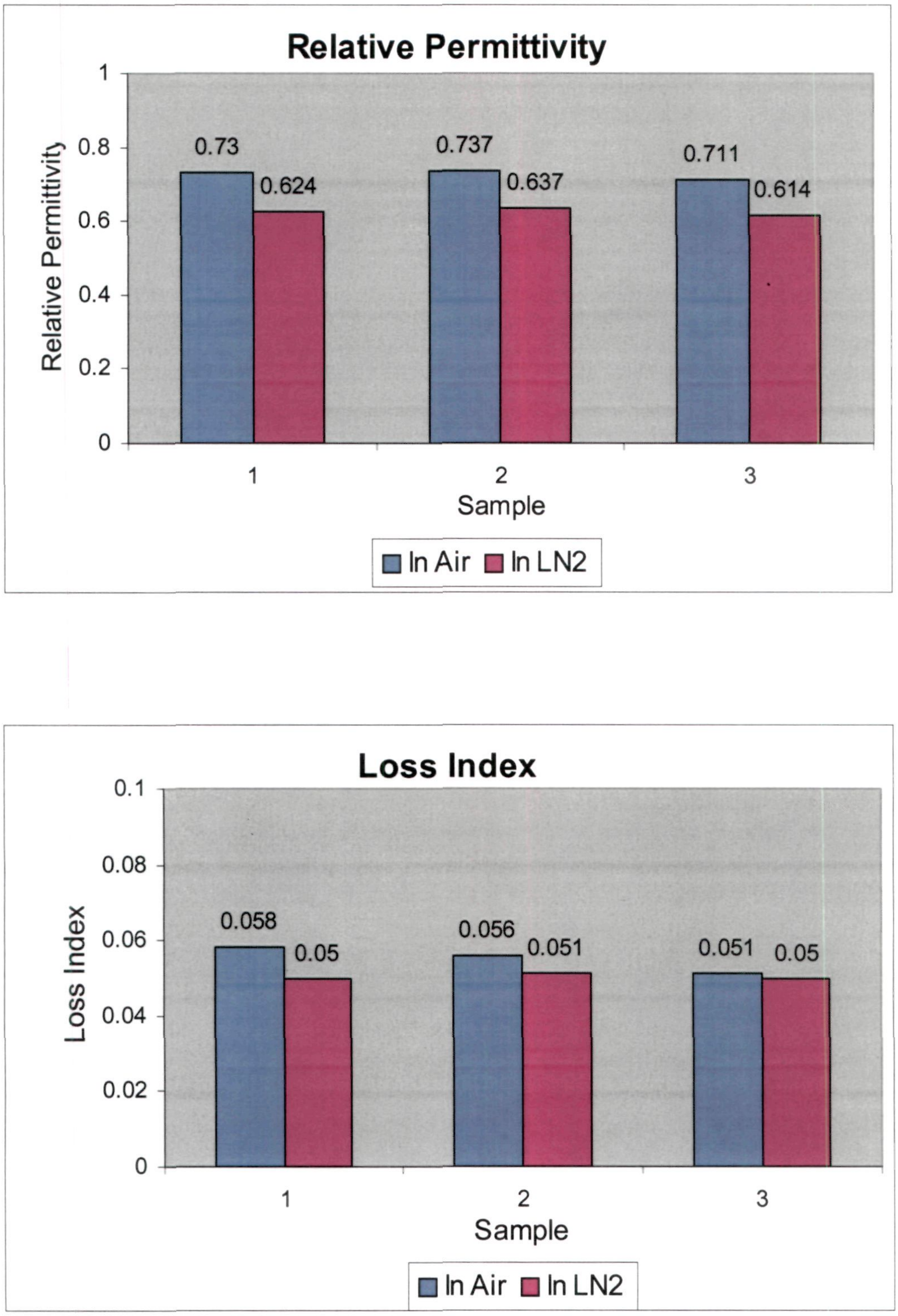


Fig.4.13: Comparison of (a) relative permittivity (b) loss index of **Presspahn** in air and in LN_2.

4.5 AREA AND VOLUME EFFECTS ON THE BREAKDOWN STRENGTH OF LN_2

Area & Volume effects on the breakdown strength of LN_2

Table 4.16-4.18 shows the observations for the breakdown voltage measurements in LN_2 using sphere-plane electrode geometry for different gaps (0.5, 1.0 & 1.5 mm) between electrodes.

Table 4.19-4.21 shows the observations for the breakdown voltage measurements in LN_2 using coaxial cylindrical electrodes for different gap lengths (3.0, 4.5 & 6.0 mm).

Table 4.22 shows the average breakdown voltage in LN_2 for sphere-plane electrode geometry for different gaps (0.5, 1.0 & 1.5 mm).

Table 4.23 shows the average breakdown voltage in LN_2 using coaxial cylindrical electrodes for different gap lengths (3.0, 4.5 & 6.0 mm).

Table 4.24 shows the maximum electric field strength E_{max}, SEA and SLV for coaxial cylindrical electrode geometry of different dimensions (L=30,100 & 350 mm; g=3.0, 4.5, & 6.0mm).

Figure 4.14 shows the ac breakdown voltage in LN_2 as a function of sphere diameter d for different gap lengths.

Figure 4.15&4.16 respectively shows ac breakdown strength in LN_2 as a function of $(SEA)_{90}$ and $(SLV)_{90}$ for coaxial cylindrical electrode configuration.

OBSERVATIONS

SPHERE- PLANE ELECTRODE GEOMETRY

S.No.	Breakdown Voltage (kV)				
	Sphere diameter			Rod diameter (6 mm)	Needle tip diameter (1 mm)
	50 mm	20mm	10mm		
1.	13.37	18.58	22.91	23.84	14.76
2.	14.65	18.64	23.34	27.13	16.23
3.	13.96	19.54	22.98	25.01	15.12
4.	14.73	17.36	25.78	26.76	14.91
5.	12.64	17.61	24.09	22.96	18.11
6.	12.98	17.85	22.71	26.13	19.56
7.	13.13	19.56	25.31	23.76	15.47
8.	13.77	17.87	24.56	24.82	19.01
9.	15.18	18.97	23.66	23.91	18.32
10.	14.97	17.86	24.21	26.54	16.31

Table 4.16(For 0.5 mm gap between Electrodes)

S.No.	Breakdown Voltage (kV)				
	Sphere diameter			Rod diameter (6 mm)	Needle tip diameter (1 mm)
	50 mm	20mm	10mm		
1.	26.51	27.01	29.46	33.62	22.19
2.	25.17	28.99	30.27	32.00	23.01
3.	25.02	28.11	30.12	32.05	22.86
4.	24.93	29.13	31.43	32.08	24.61
5.	25.86	28.43	29.98	33.92	25.01
6.	26.70	27.91	30.64	31.95	22.28
7.	26.61	28.01	30.32	33.11	22.48
8.	25.89	27.97	31.01	32.86	23.40
9.	26.41	29.03	29.91	32.91	22.11
10.	25.78	28.10	30.18	33.01	24.08

Table 4.17 (For 1.0 mm gap between Electrodes)

S.No.	Breakdown Voltage (kV)				
	Sphere diameter			Rod diameter (6 mm)	Needle tip diameter (1 mm)
	50 mm	20mm	10mm		
1.	36.28	39.21	41.26	42.21	30.15
2.	36.14	38.06	40.77	42.15	29.94
3.	37.21	39.11	41.08	43.11	31.61
4.	37.78	37.76	40.85	42.46	30.68
5.	36.68	38.25	41.27	41.33	29.83
6.	36.91	38.37	40.23	42.19	29.76
7.	38.02	38.12	41.57	42.35	30.15
8.	35.80	37.41	39.96	41.77	30.29
9.	36.12	37.99	40.17	42.15	31.57
10.	36.69	38.29	40.44	41.67	30.42

Table 4.18 (For 1.5 mm gap between Electrodes)

COAXIAL CYLINDRICAL ELECTRODE GEOMETRY

S.No.	Breakdown Voltage (kV)		
	For Effective Electrode Length 'L'		
	30 mm	100mm	350 mm
1.	101.20	98.65	91.50
2.	102.75	99.50	92.80
3.	105.3	100.20	90.73
4.	104.58	97.03	90.56
5.	103.56	98.76	94.56
6.	103.52	95.30	95.67
7.	104.00	98.43	92.50
8.	106.20	97.67	93.50
9.	103.50	100.78	96.80
10.	105.50	97.23	95.78

Table 4.19 (For 3.0 mm Gap Length)

S.No.	Breakdown Voltage (kV) For Effective Electrode Length 'L'		
	30 mm	100mm	350 mm
1.	116.00	104.45	98.67
2.	115.89	106.67	99.46
3.	107.67	106.45	97.88
4.	108.45	104.44	99.34
5.	106.43	103.55	98.45
6.	109.78	104.89	102.50
7.	110.34	105.67	101.45
8.	111.45	104.34	102.45
9.	114.45	105.88	101.33
10.	108.56	104.33	100.56

Table 4.20(For 4.5 mm Gap Length)

S.No.	Breakdown Voltage (kV)		
	For Effective Electrode Length 'L'		
	30 mm	100mm	350 mm
1.	115.78	112.34	105.85
2.	117.89	113.00	104.22
3.	116.98	114.8	104.56
4.	117.98	115.2	103.67
5.	115.89	112.67	105.78
6.	118.9	114.80	103.67
7.	118.45	111.00	105.00
8.	119.6	110.67	106.89
9.	120.45	113.89	107.23
10.	120.50	112.78	104.67

Table 4.21(For 6.0 mm Gap Length)

Gap between Electrodes (mm)	Average Breakdown Voltage (kV)				
	Sphere diameter			Rod diameter (6 mm)	Needle tip diameter (1 mm)
	50mm	20mm	10mm		
0.5	13.94	18.38	23.95	25.08	16.78
1.0	25.89	28.27	30.33	32.75	23.20
1.5	36.76	38.26	40.76	42.14	30.47

Table-4.22: Average Breakdown Voltage for Sphere-Plane Electrode Geometry

Gap between Electrodes (mm)	Average Breakdown Voltage (kV)		
	For Effective Electrode Length 'L'		
	30 mm	100mm	350 mm
3.0	104.01	98.36	93.44
4.5	110.90	105.07	100.21
6.0	118.24	113.12	105.15

Table-4.23: Average Breakdown Voltage for Coaxial Cylindrical Electrode Geometry

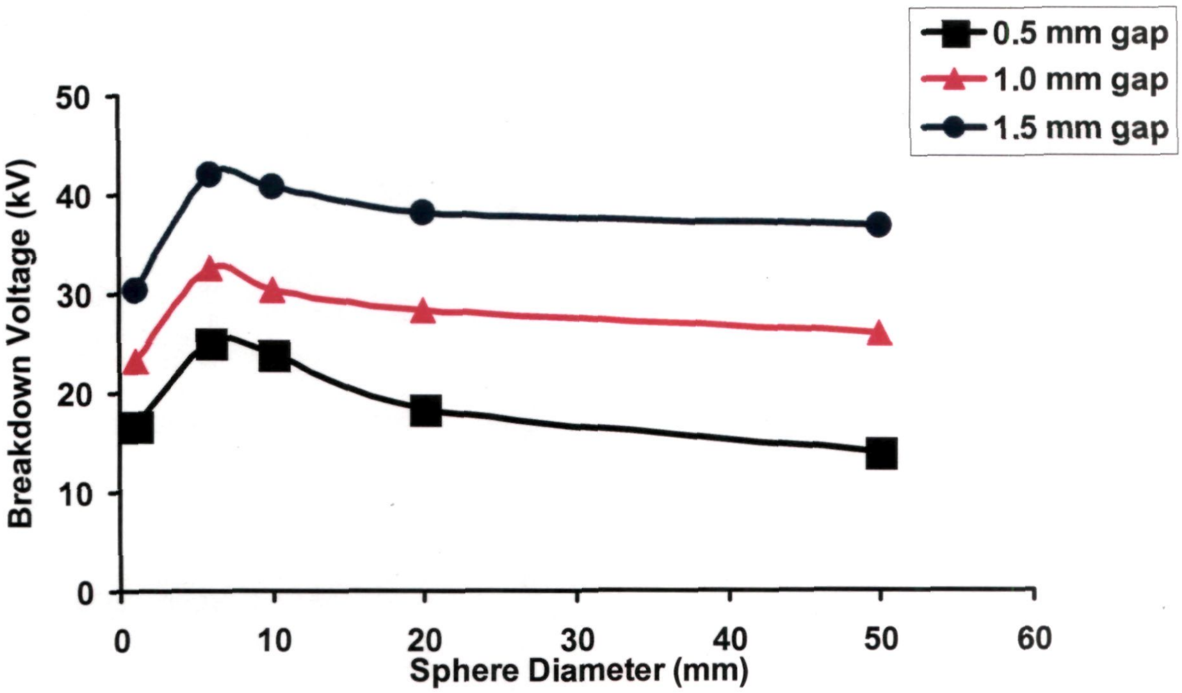
Gap between Electrodes (mm))	For Effective Electrode Length 'L'		
	30 mm	100mm	350 mm
3.0	E_{max}=20.407 SEA=3015.92 SLV=5659.52	E_{max}=19.297 SEA=10053.09 SLV=18865.06	E_{max}=18.333 SEA=35185.83 SLV=66027.74
4.5	E_{max}=16.214 SEA=2450.44 SLV=3736.16	E_{max}=15.361 SEA=8168.14 SLV=12453.89	E_{max}=14.651 SEA=28588.49 SLV=43588.62
6.0	E_{max}=14.993 SEA=1884.95 SLV=2210.75	E_{max}=14.343 SEA=6283.18 SLV=7369.16	E_{max}=13.333 SEA=21991.14 SLV=25792.08

Note: Units for E_{max}. SEA and SLV are kV/mm, mm^2 and mm^3 respectively.

Table 4.24

S.No.	Breakdown Voltage (kV)		
	For Effective Electrode Length 'L'		
	30 mm	100mm	350 mm
1.	115.78	112.34	105.85
2.	117.89	113.00	104.22
3.	116.98	114.8	104.56
4.	117.98	115.2	103.67
5.	115.89	112.67	105.78
6.	118.9	114.80	103.67
7.	118.45	111.00	105.00
8.	119.6	110.67	106.89
9.	120.45	113.89	107.23
10.	120.50	112.78	104.67

Table 4.21(For 6.0 mm Gap Length)



0.5 mm gap
1.0 mm gap
1.5 mm gap
Breakdown Voltage (kV)
0
10
20
30
40
50
0
10
20
30
40
50
60
Sphere Diameter (mm)

Figure 4.14

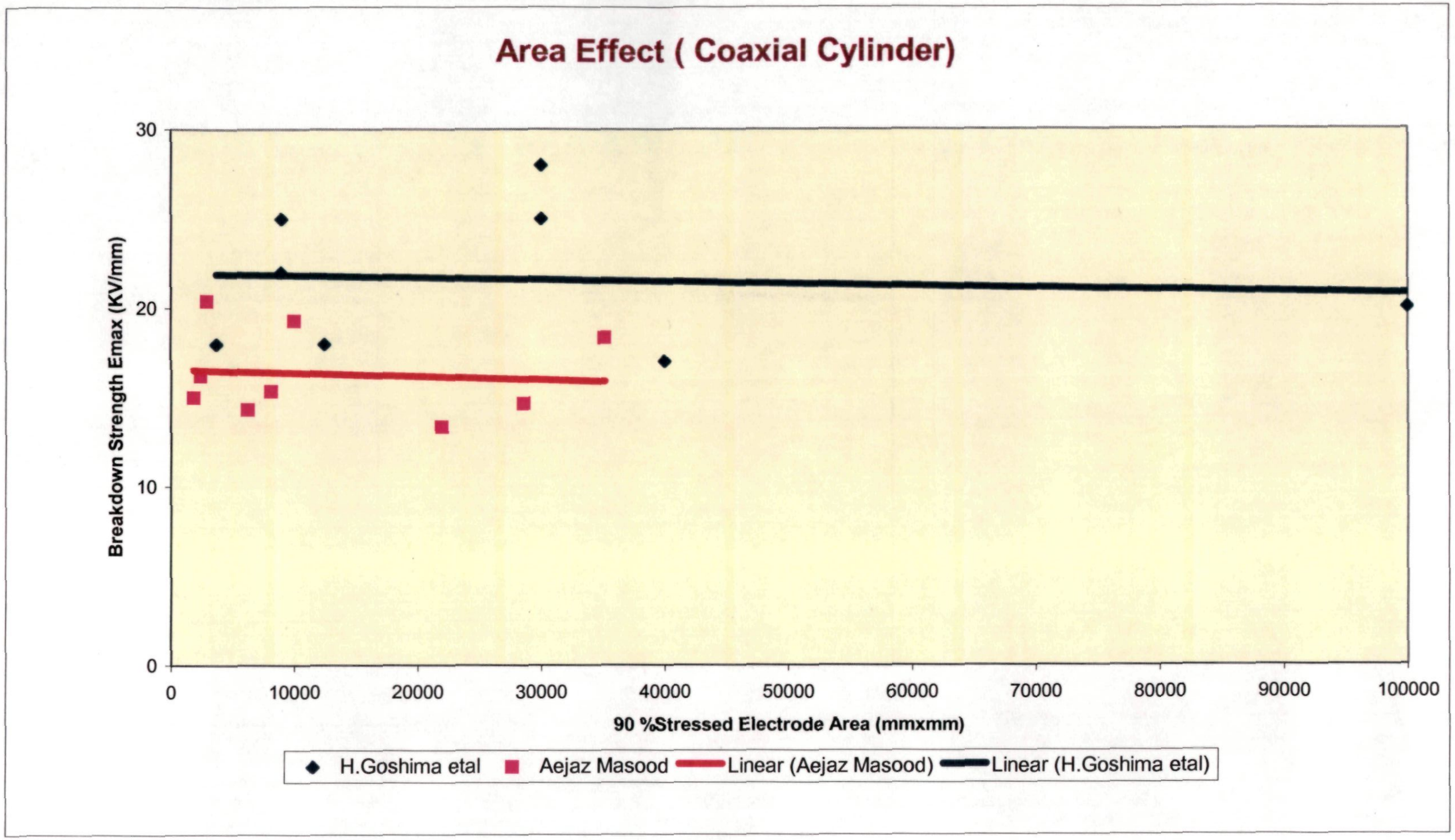

Area Effect (Coaxial Cylinder)
Breakdown Strength Emax (KV/mm)
30
20
10
0
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
90 %Stressed Electrode Area (mmxmm)
H.Goshima etal
Aejaz Masood
Linear (Aejaz Masood)
Linear (H.Goshima etal)

FIGURE 4.15

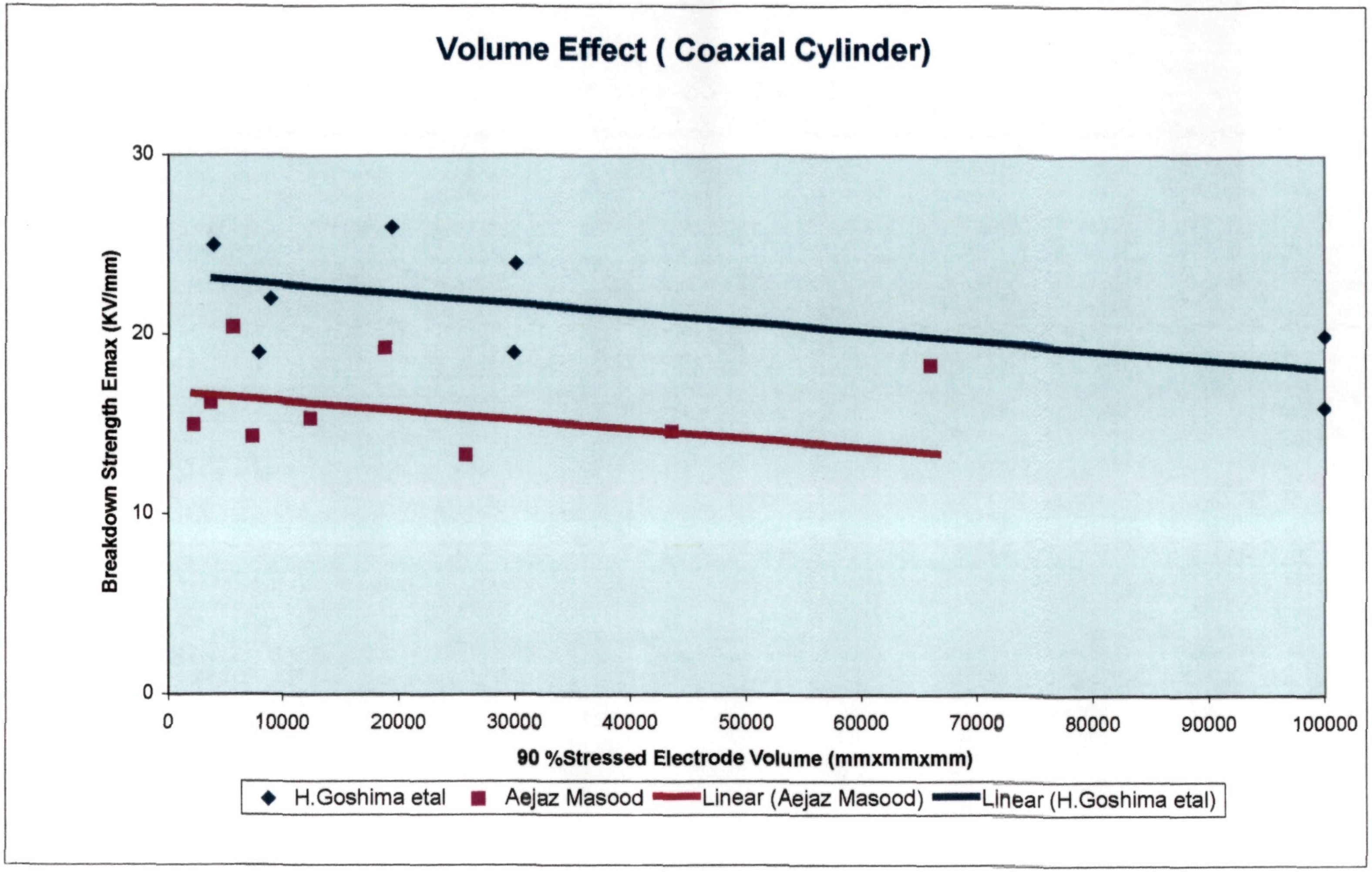

Volume Effect (Coaxial Cylinder)
Breakdown Strength Emax (KV/mm)
30
20
10
0
0
10000
20000
30000
40000
50000
60000
70000
80000
90000
100000
90 %Stressed Electrode Volume (mmxmmxmm)
H.Goshima etal
Aejaz Masood
Linear (Aejaz Masood)
Linear (H.Goshima etal)

FIGURE 4.16

CHAPTER-5

DISCUSSIONS

5.1 AC BREAKDOWN STRENGTH OF LN_2

The highest breakdown strength of LN_2 was found to be 29 kV/mm for plane-plane electrodes configuration, while the minimum strength observed was 9.6 kV/mm for needle-needle configuration (Figure 4.01). The other combinations of electrodes yielded intermediate values of dielectric strength depending upon the field condition. It appears that the breakdown strength values obtained are non-intrinsic to LN_2 and are averaged by the presence of ionic impurities and very fine particles of ice, which may get introduced during the filling up of the cryostat. It is observed that, in LN_2 also, the breakdown strength goes on decreasing as the gap length increases, for example fon plane –plane electrodes the breakdown strength decreases from 29 kV/mm to 18 kV/mm when the gap length changes from 1 mm to 5 mm. This effect is most pronounced in the case of the needle-needle configuration. Hence, it can be inferred that the ac breakdown strength of liquid nitrogen depends not only on gap length but also on the electrode geometry, a phenomena commonly observed in gases and other liquid dielectrics. [118]

5.2 BREAKDOWN STRENGTH OF SOLID DIELECTRICS IMMERSED IN LN_2

Breakdown strength of solid insulating materials was found to improve when dipped in liquid nitrogen with significant increases being observed for porous materials such as cotton tape, Empire tape, Kraft paper, leatheroid paper, varnished paper while the increase in the breakdown strength was comparatively low for non-porous materials

Like PVC tape, Minimax, Perspex, Tyvek, Mica sheet, PVC sheet of cable and polyester film with the only exception being bakelite. (Figure 4.02)

It is seen that the breakdown strength of dielectric materials in LN_2 is highly dependent on the porosity or material density of the samples. Thus the observed results may be broadly divided into two groups, i.e. the breakdown strength of porous materials and breakdown strength of non- porous impervious materials in LN_2. For porous materials, liquid nitrogen performs the role of impregnating the dielectrics, filling up the cavities & voids, thereby enhancing the breakdown strength. Since the relative permittivity of liquid nitrogen is in the range of 1.3-1.4 and it fills the void/cavity at exceedingly low temperature, where the ionic mobility is also low, resulting in higher breakdown strength. In case of non-porous materials the increase in breakdown strength is not so significant and it may be due to lowering of the temperature only.

5.3 BREAKDOWN OF CRYOGENIC AIR UNDER NON-UNIFORM FIELDS

The ac breakdown voltages observed for air at cryogenic temperature under non-uniform field conditions show only a slight improvement (10-20%) over the breakdown voltage for air at room temperature. This may be accounted for by reduced mobility of the carriers at cryogenic temperature.

Sphere-to-Sphere gaps less than their radii spark approximately at the same potential as uniform field gaps. In case of coaxial electrode system having inner and outer electrode radii of R_i and R_o respectively the field utilization factor is given by

$$U= R_i/(R_o-R_i)*\left[\ln\ [R_o/R_i]\right]$$

It has been shown earlier [109] that the effect of field utilization factor can be evaluated by measuring the sparking potentials in uniform and non-uniform fields under similar conditions. Also for practical use in a non-uniform field in which the field utilization factor is U, the sparking potential was obtained as a fraction $f = U^{0.85}$ of the uniform field sparking potential for the same gap under similar conditions of gas [109].

Table 4.13 shows the breakdown voltages in air at room temperature reported earlier by Ritz [108] and with spherical electrodes as reported by Toyota [76].

Table 4.14 shows the breakdown voltages in air at cryogenic temperature using spherical electrodes [76] and also values after multiplication by $U^{0.85}$. The Table 4.14 also gives a comparison of the values obtained in the laboratory using coaxial cylinders.

These breakdown voltages for uniform fields multiplied by the field utilization factor are evaluated and compared with the results obtained for non-uniform fields and have been plotted in Figures 4.03 & 4.04 respectively. It is observed that the application of field utilization factor $U^{0.85}$ holds good even for air at cryogenic temperature.

The breakdown strength of air at cryogenic temperature (Table 4.12) is quite low as compared to breakdown strength of liquid nitrogen [106]. It suggests that the, insulation of high temperature superconductors with cryogenic air offers no advantages when compared to high temperature superconductors insulated with liquid nitrogen due to superior breakdown strength of LN_2 as reported in a recent study [106]. However, it may be easy to maintain the temperature and pressure of air in the cylinder when compared to direct LN_2 cooling.

5.4 RELATIVE PERMITTIVITY AND LOSS INDEX OF SOLID DIELECTRICS IMMERSED IN LN_2

The values of relative permittivity and loss index measured for a variety of dielectrics are presented in Figures 4.05 to 4.13. It is known that LN_2 is a non-polar liquid and exhibits very low but measurable loss tangent of the order of 10^{-5} at power frequency. The dielectric loss in liquids or solids or in their combination may be associated with one or more of the following mechanisms (i) dipole relaxation (ii) space charge or interfacial polarization and (iii) ionic oscillation [119].

The losses due to the first two mechanisms are functions of frequency and temperature while the loss due to ionic oscillation depends on the type of dielectric, its thickness and ionic mobility. LN_2 being a non-polar liquid is not expected to show any dielectric loss at power frequencies. However, Jefferies and Mathes [120] measured the dielectric loss of LN_2 and found it to be practically constant for large gaps. This loss is mainly due to presence of ionic impurities and fine particles of ice, which are difficult to avoid during the filling up process of the cryostat. However, once a solid dielectric is dipped in LN_2 the quantum of dielectric loss of the composite system will attain a value which shall lie between the limits imposed by loss index of LN_2 on one side and loss index of solid dielectric on the other. The loss index will depend on dipole relaxation and interfacial polarization. The extent of the loss will also depend on the type of dielectric and its properties namely porosity, material density and whether the solid dielectric is polar or non-polar, of course the effect being pronounced for polar dielectrics.

An examination of Figures 4.05 to 4.13 shows that in general the decrease in dielectric loss index is two fold under LN_2 environment i.e. due to reduction in both relative permittivity and loss tangent. The percentage reduction in loss index for solids dipped in LN_2 is more for cellulosic insulating materials as compared to impervious materials.Figures 4.05 to 4.09 represent the loss index of crepe paper, Kraft paper and pressboard with material densities 0.9,1.01,1.28 to 1.04gm/cm^3 respectively. It is observed that less is the material density; more pronounced is the reduction in the measured loss index. This can be explained on the basis of extent of impregnation by LN_2. Further, the reduction may be attributed to a change in lattice structure due to low temperature of LN_2 and due to formation of ice of the residual moisture present in the sample.

Figures 4.10 to 4.13 represent the loss index of polythene-coated paper, Perspex, thermoplastic (nylon6) and pressphan. In these cases the decrease in loss index of dielectrics dipped in LN_2 is not so pronounced because LN_2 remains only on the surface and is not able to impregnate the dielectrics.In general it may be concluded that the relative permittivity and loss tangent of the solid dielectrics decrease when they are dipped in LN_2 but the amount of decrease is a function of porosity/material density of the dielectric.

5.5 CORRELATION OF VOLUME RESISTIVITY AND LOSS INDEX WITH BREAKDOWN VOLTAGE OF INSULATING MATERIALS UNDER LN_2

The theory behind dielectric breakdown has always been to a great extent equal part of speculation, art and science. The interaction of fields, particles and atoms on a microscopic level is so complex that exact quantum mechanical solution to all but the simplest atomic structure has been impossible. Therefore, the equally complex phenomena of dielectric strength continues to be attacked on an empirical level using known microscopic effects and results to better understand the mechanism of breakdown.

A myriad of factors, which might influence dielectric strength, could be listed. These include intrinsic material properties, a host of external environmental factors and assorted test conditions that may exist. However, the list can be shortened considerably if the environmental factors and test conditions are kept constant. If this were the case, then a list of intrinsic material properties, which might affect the dielectric strength, would result. Such a result is given below.

1. ξ_r = dielectric constant
2. Tanδ= dissipation factor or loss tangent
3. E_i = ionization energy for electron removal from the molecule= V_i e

   where V_i= ionization potential and e= electronic charge

4. t = sample thickness
5. μ= Mobility of charge carriers available
6. n = number of charge carriers available
7. l = mean free path among molecules
8. V_f = Free volume of the material

The stage is set for dielectric failure when the average kinetic energy of the charge carriers within a material approaches that of the ionization energy required to remove electrons from the molecules. This average kinetic energy results from the charge carriers being exposed to an electric field, E_f, with freedom to move about over a mean free path, l. Determining how much each of the variables listed above relate to this phenomena then becomes the major task in explaining dielectric breakdown.

Many of the parameters such as the first four listed above (ξ_r, Tanδ, E_i, t) can be measured in a relatively straightforward manner. However, the others require measurement via a more indirect path.

Mobility of charge carriers is very difficult to define [121]. However, if the number of charge carriers are known, the volume resistivity measurement can be used to determine μ through the equation $\rho=1/ne\mu$.

The mean free path, l, of a free electron in a material is the next variable to be considered. This variable is dependent upon the free volume of a material (V_f) and the molecular agitation within the material. Both of these are temperature dependent. The increase in free volume with temperature leads to an increase in the mean free path. However, the increased molecular agitation at high temperatures tends to decrease this path. Thus, the measurement and calculation of this parameter is most difficult.

Having examined the intrinsic material factors that might affect dielectric strength, an attempt is made to relate these to the energy required for breakdown. The kinetic energy which an electron acquires when subjected to a field E_f, is dependent upon the mean free path between collisions, l. If most of the energy is absorbed by the molecule when the collision occurs then the kinetic energy is:

$$K.E. = (E_f)\,(l)$$

E_f can be calculated using the equation [122]:

$$E_f = V\,[\xi_r+2]/3t$$

where V=applied voltage, t= thickness & ξ_r=dielectric constant

Thus, the maximum energy an electron can posses before it will ionize a molecule is:

$$E_i = E_f l = l\,V\,[\xi_r+2]/3t \quad \text{eV}$$

By rearranging terms it can be seen that the maximum voltage that could be applied across a dielectric before failure occurs might include the term:

$$\frac{E_i}{l\,[\xi_r+2]/3t}$$

$$\text{or } V_{max} = f\,[E_i,\, l\,[\xi_r+2]/3t]$$

This term, along with the directly measurable parameters previously discussed, provide the potential basis for determining an empirical relationship involving the Dielectric Strength = $f\,[E_i,\, l\,(\xi_r+2)/3t,\, \rho,\, \mathrm{Tan}\delta]$

The mean free path l should equal to the cube root of the free volume, V_f since $\rho = 1/ne\mu$ where $\mu = f\,(V_f)$. However, since ρ also depends on n, an unknown quantity, both terms l and ρ should be included in the final equation relating dielectric strength to other material properties. Regretfully the experiments discussed in this thesis do not include studies on two of the parameters given in the relationship namely E_i and l.

With these limitations in mind and using test samples of the same thickness in a group, which is again an approximation to eliminate t from the equation, the dielectric strength relationship to be investigated becomes:

$$\textbf{Dielectric Strength} = f\,(\xi_r, \rho, \tan\delta)$$

The observations & calculations performed on the basis of above said equation are given in the text to follow.

Table 5.1

Material	Volume Resistivity ρ_v	Relative Permittivity ζ_r (observed in liquid nitrogen)	Tanδ (observed in liquid nitrogen)	ζ_r * Tanδ	x = Log [ρ_v / ζ_r Tanδ]	y = Observed breakdown strength in LN_2(KV/mm)
Crepe Paper	10^{14} Ω-cm	1.055	.077	.081	16.09	50
		1.149	.077	.089	16.05	48
		0.990	.062	.061	16.21	51
Kraft Paper	10^{14} Ω-cm	1.06	.053	.056	16.25	54
		1.03	.059	.061	16.21	55
		1.03	.058	.060	16.22	52
Pressboard I	10^{12} Ω-cm	1.65	.094	.155	13.8	48
		1.58	.09	.142	13.84	50
		1.6	.097	.155	13.8	49
Pressboard II	10^{12} Ω-cm	1.403	.072	.101	13.99	55
		1.679	.049	.082	14.08	58
Pressboard III	10^{12} Ω-cm	1.58	.025	.039	14.4	60
		1.172	.055	.065	14.18	59
Polythene coated paper(one sided)	10^{16} Ω-cm	2.093	.064	.133	17.87	60
		2.198	.059	.129	17.88	55
Presspahn	10^{13} Ω-cm	.624	.08	.05	15.30	78
		.637	.08	.051	15.29	80
		.614	.081	.05	15.30	85
Mica	10^{16} Ω-cm	.199	.086	.017	18.76	88
		.197	.085	.016	18.79	80
		.244	.077	.0187	18.72	85
Bakelite	10^{13} Ω-cm	2.858	.064	.1829	13.73	43
		2.605	.062	.161	13.79	45
		2.978	.059	.175	13.75	47
Asbestos	16×10^{10} Ω-cm	1.127	.090	.102	12.19	35
		1.095	.091	.099	12.20	34
		1.104	.086	.095	12.22	36

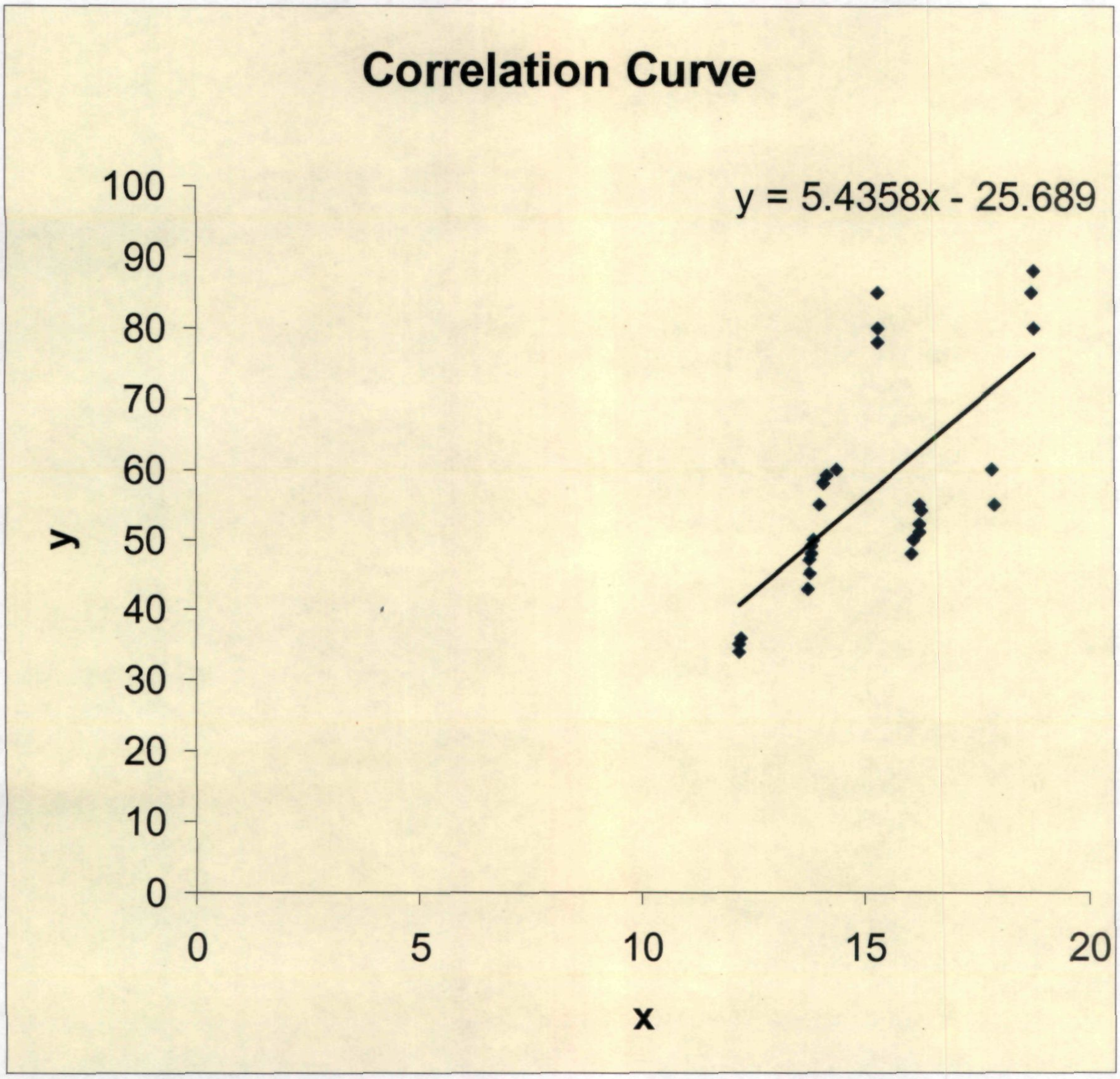

Correlation Curve
y = 5.4358x - 25.689
100
90
80
70
60
50
40
30
20
10
0
y
0
5
10
15
20
x

Figure 5.1

Measurements of relative permittivity and $\tan\delta$ were carried out on ten different samples of insulating materials.

Table 5.1 shows the calculations performed on the basis of observed values of relative permittivity and $\tan\delta$ in the medium of liquid nitrogen for different samples of insulating materials. The table also shows the observed values of breakdown strength of materials in the medium of liquid nitrogen. The breakdown voltage was measured using the same procedure described in section 3.2.Figure 5.1 shows the graph drawn between the observed breakdown strength vs. Log $[\rho_v / \zeta_r \operatorname{Tan}\delta]$. From the plot the equation of the straight line obtained in the form of **y=mx+b** is given as

$$\textbf{Breakdown strength} = \mathbf{5.4358\ Log\ [\rho_v / \zeta_r\ Tan\delta] - 25.689}$$

The following Table 5.2 shows the comparison between the observed values of the breakdown strength and calculated values of the breakdown strength using the obtained equation. The table also shows the %error in the breakdown strength.

Table 5.2

Material	x = Log [ρ_v / ζ_r Tanδ]	y = Observed breakdown strength in LN_2(KV/mm)	Calculated breakdown strength from BDS = 5.4358 Log [ρ_v / ζ_r Tanδ] - 25.689	% Error
Crepe Paper	16.09	50	61.77	23.54
	16.05	48	61.77	28.68
	16.21	51	62.42	22.39
Kraft Paper	16.25	54	62.42	16.0
	16.21	55	62.42	13.49
	16.22	52	62.47	20.13
Pressboard I	13.8	48	49.32	2.75
	13.84	50	49.54	0.92
	13.8	49	49.32	0.65
Pressboard II	13.99	55	50.35	8.45
	14.08	58	50.84	12.34
Pressboard III	14.4	60	52.58	12.36
	14.18	59	51.39	12.89
Polythene coated paper(one sided)	17.87	60	71.44	19
	17.88	55	71.50	30
Presspahn	15.30	78	57.47	26.32
	15.29	80	57.42	28.22
	15.30	85	57.47	32.38
Mica	18.76	88	76.28	13.31
	18.79	80	76.44	4.45
	18.72	85	76.06	10.51
Bakelite	13.73	43	48.94	13.81
	13.79	45	49.27	9.48
	13.75	47	49.05	4.36
Asbestos	12.19	35	40.57	15.91
	12.20	34	40.62	19.47
	12.22	36	40.73	13.13

Since it has not been possible in this work to measure volume resistivity, its value has been taken from the available literature [23,56,58,84] but still the designers can use the equation proposed. The volume resistivity will be affected by liquid nitrogen to the extent it is able to penetrate into the volume of the material. So for porous materials volume resistivity shall increase and for non-porous plastic materials it may not change to great extent.

Further each of electrical properties namely ρ_v, ζ_r and Tanδ are temperature dependent. Therefore each property should first be studied as a function of temperature. Thereafter the effect of temperature can be normalized out of the data or included as a shift factor in search of a best-fit equation.

5.6 AREA & VOLUME EFFECTS ON THE BREAKDOWN STRENGTH IN LN_2

The relationship between maximum electric field strength and the sphere diameter has been reported earlier [123] and it was shown that maximum electric field strength decreases with an increase in electrode diameter. Therefore it is expected that if the breakdown voltage is to be determined only by the maximum electric field strength, the breakdown voltage would increase because of more uniformity in the electric field distribution.

However the experimental results as can be seen from Figure 4.14, show that the breakdown voltage decreases as the sphere diameter increases in the range of d > 10mm. Thus the experimental results for sphere to plane electrodes suggest that the breakdown characteristics in liquid nitrogen is influenced by the area and volume effects and can be analyzed in these terms.

While analyzing the area and volume effects on breakdown strength, the area and volume affecting the breakdown strength should be determined. In the present analysis, the electrode area and the liquid volume where the electric field exceeds 90% of maximum electric field strength are taken as the stressed electrode area and stressed liquid volume being defined as $(SEA)_{90}$ and $(SLV)_{90}$ respectively.

For the investigation of area and volume effects over a wide range of electrode size, two kinds of electrode configurations; sphere to plane and coaxial cylindrical electrodes were used. For the sphere to plane electrode configuration, $(SEA)_{90}$ and $(SLV)_{90}$ was varied with the sphere diameter and the gap length whereas for the coaxial cylindrical electrodes $(SEA)_{90}$ and $(SLV)_{90}$ was varied with the gap length (g) and the electrode length (L).

For the present sphere to plane electrode configurations with different diameters and gap lengths, $(SEA)_{90}$ varied from 10^{-1} to 10^2 mm^2 and $(SLV)_{90}$ varied from 10^{-3} to 10^2 mm^3 respectively [34].

The, $(SEA)_{90}$ and $(SLV)_{90}$ for coaxial cylindrical electrodes configurations can be calculated as follows:

$$(SEA)_{90} = 2a \Pi L \qquad \text{for } a < 0.9b$$

$$(SLV)_{90} = 19/81 * (\Pi L a^2) \quad \text{for } a \leq 0.9b$$

Also maximum electric field strength E_{max} for the coaxial cylindrical electrodes is given by

$$E_{max} = \frac{V}{a.\ln(b/a)}$$

where V is applied voltage, a and b are the inner and outer cylindrical electrode radii, respectively.

It can be seen from Table 4.24 that the present coaxial cylindrical electrodes allowed the $(SEA)_{90}$ and $(SLV)_{90}$ to vary from 1.8×10^3 to 3.5×10^4 mm^2 and from 2.2×10^3 to 6.6×10^4 mm^3 respectively. The results are plotted in Figure 4.15 & 4.16 and are compared with results reported by H.Goshima etal [34]. The results are found to be quite in agreement with the earlier reported results.

It can thus be seen from Figure 4.15 & 4.16 respectively that the ac breakdown strength in liquid nitrogen decreases as the $(SEA)_{90}$ and $(SLV)_{90}$ increases. Both the area and volume effect cause decrease of breakdown strength in LN_2.

CHAPTER-6

SUMMARY OF CONCLUSION AND FUTURE WORK

Summary of Conclusion & Future Work

Extensive experimental work was carried out to assess the:

I. Breakdown Voltage of liquid nitrogen and its dependence on various electrode configurations.

II. Breakdown strength of solid dielectrics in liquid nitrogen medium.

III. Loss index of solid dielectrics immersed in liquid nitrogen.

IV. Breakdown of cryogenic Air under Non-Uniform Fields

V. Area & Volume effects on the breakdown strength of LN_2

The experimental results reported earlier in Chapter 3, 4 & 5 lead us to conclude the following:

The highest breakdown strength of LN_2 was found to be 29 kV/mm for plane-plane electrodes configuration, while the minimum strength observed was 9.6 kV/mm for needle-needle configuration (Figure 4.01). The other combinations of electrodes yielded intermediate values of dielectric strength depending upon the field condition. It appears that the breakdown strength values obtained are non-intrinsic to LN_2 and are averaged by the presence of ionic impurities and very fine particles of ice, which may get introduced during the filling up of the cryostat. It is observed that, in LN_2 also, the breakdown strength goes on decreasing as the gap length increases, for example for plane –plane electrodes the breakdown strength decreases from

29 kV/mm to 18 kV/mm when the gap length changes from 1 mm to 5 mm. This effect is most pronounced in the case of the needle-needle configuration. Hence, it can be inferred that the ac breakdown strength of liquid nitrogen depends not only on gap length but also on the electrode geometry, a phenomena commonly observed in gases and other liquid dielectrics.

Breakdown strength of solid insulating materials was found to improve when dipped in liquid nitrogen with significant increases being observed for porous materials such as cotton tape, Empire tape, Kraft paper, leatheroid paper, varnished paper while the increase in the breakdown strength was comparatively low for non-porous materials Like PVC tape, Minimax, Perspex, Tyvek, Mica sheet, PVC sheet of cable and polyester film with the only exception being bakelite. (Figure 4.02)

It is seen that the breakdown strength of dielectric materials in LN_2 is highly dependent on the porosity or material density of the samples. Thus the observed results may be broadly divided into two groups, i.e. the breakdown strength of porous materials and breakdown strength of non- porous impervious materials in LN_2. For porous materials, liquid nitrogen performs the role of impregnating the dielectrics, filling up the cavities & voids, thereby enhancing the breakdown strength. Since the relative permittivity of liquid nitrogen is in the range of 1.3-1.4 and it fills the void/cavity at exceedingly low temperature, where the ionic mobility is also low, resulting in higher breakdown strength. In case of non-porous materials the increase in breakdown strength is not so significant and it may be due to lowering of the temperature only.

The experiment conducted for air at cryogenic temperature using coaxial geometry shows a slight improvement 10-20% over the breakdown voltage of air at room temperature. Also the experiment confirms that the breakdown in liquid nitrogen & air at cryogenic temperature is field dependent & it has been possible to apply field utilization factor $U^{.85}$ to convert the results obtained under uniform field conditions[109]. This shows that the Paschen's law is valid even at cryogenic temperatures.

The most interesting result reported in Chapter 4 deals with the relative permittivity and loss index of solid dielectrics immersed in LN_2. The results show that the loss index in case of cellulosic material is more pronounced & marked compared to non-cellulosic materials. The amount of decrease is a function of porosity & material density.

All the above results lead to a situation where it is thought that, it should be possible to correlate the loss index, volume resistivity with the breakdown voltage.

The relation arrived is written as

$$\text{Breakdown strength} = 5.4358 \text{ Log } [\rho_v / \zeta_r \text{ Tan}\delta] - 25.689$$

Here however it is pointed out that the volume resistivity of the material used in the above expression was measured at room temperature. This might lead to some error in the computed breakdown voltage using the relation. However this equation is a handy tool for quick estimation of breakdown voltage of solid dielectrics dipped in LN_2

The study of breakdown strength, taking into account the area and volume effects of electrode, indicates that the area and volume effect cause decrease of breakdown strength in liquid nitrogen.

In general the data presented demonstrates the behavior of solid dielectrics in liquid nitrogen environment with particular reference to the effect on their breakdown strength and loss index. The data presented and analyzed recommend the use of porous dielectrics for insulating high temperature superconductors.

However a more comprehensive study is desired regarding partial discharge phenomena, mechanical and thermal characteristics and ageing process of solid insulants dipped in liquid nitrogen, in order to predict the breakdown strength. Also it is desired that volume resistivity of solid dielectrics to be used as spacers be determined in the liquid nitrogen medium.

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APPENDIX-I

Properties of Electrical Insulating Materials at Cryogenic Temperatures

General Properties:

Electrical insulation at cryogenic temperature is subjected to all constraints of conventional equipment and additional ones linked directly to the extremely cold environment. For example:

- The design of components has to be such that it has to allow for a large physical contraction, not necessarily identical for all components.
- Cooling/heating cycles must not change the quality of the insulation, nor should they cause deterioration.
- Losses, whatever their origin, have to be eliminated by the cooling system. For this reason, the refrigerant is often part of the electrical insulation as well.

Another element that must absolutely be taken into account is specific to superconducting systems: the quenching, in other words, the sudden transition from the superconducting state to the non- superconducting state. Indeed the conductor must be designed to withstand such situations but this is not without influences on complete system, including the insulation.

Mechanical & Thermal Properties:

Mechanical properties (strength, elongation, modulus, creep and fatigue) and thermal properties (contraction, specific heat and conductivity) of conventional insulating materials (paper, plastic etc) at cryogenic temperature have been thoroughly measured and discussed already.

However to construct practical, stable superconducting magnets, new insulating materials are indispensable in the shape of tapes, spacers etc.

Among the mechanical and thermal properties, thermal contraction (300k to 4k) is the most important. Thermal contraction should be small and in every direction.

To attain such low thermal contractions several methods have been employed amongst them is to increase the glass fiber content as high as 74% volume in the composite insulating material. However the resulting heat generation in these composite insulating materials should be investigated in more detail.

Partial Discharges:

One of the main forms of electrical degradation of insulating materials subjected to high fields at normal temperatures is partial discharge (PD). Similar mechanisms of insulating failure can also occur at cryogenic temperatures. PD can:

- occur in liquids, generating gas filled bubbles;
- be generated at interfaces between solid and fluid insulation to produce conducting paths known as tracking and
- occur in fluid and gas filled cavities within solid insulation. Prolonged PD activity erodes the insulation surface and can eventually initiate an electrical tree.

The number and amplitude of the PD's tend to increase rapidly with voltage upto maximum values, which depend upon the size of the butt gap or cavity. They also increase with time and persist at lower voltages to give extinction voltages as low as 20% of the inception value.

Pressurizing the insulation system prevents the bubbles from occurring, greatly reduces the PD intensity and raises the inception stress. In a practical system it is important to operate at stresses below the PD extinction level.

There have been several studies to evaluate the life characteristics of model cryogenic insulation system subjected to PD's. Times to failure have been measured for sphere/plane electrode geometry. Life curves were the plotted to determine the exponent 'n' of the well-known inverse power law equation:

$$V^n L = \text{constant}$$

Where V is the voltage or stress and L is the time to failure; the larger the value of n the more resistant the insulation system is to PD's. The life exponent n expresses the degree to which life is shortened by prolonged operation above the chosen working stress. A very large value of n represents a material for which a small increase in the stress cause a dramatic decreases in lifetime. Such a material would be sensitive to over-voltages. It would probably be necessary to operate a cable with a high 'n' value at stresses well below inception.

Values of n vary between 5 and 10 for LHe and between 10 and 50 for LN_2 immersed polyethylene and polypropylene.

However, life tests at cryogenic temperatures are costly and difficult to maintain for long periods. As a result, tests longer than 30 days are rare. Thus extrapolation of the data obtained from tests lasting several days to the lifetime of actual equipment, say 30 years, can introduce large errors and significant safety factors must be built in.

Analysis of materials exposed to PD's at cryogenic temperatures show discharge patterns. Repeated discharges can cause erosion and eventual puncture.

Estimates at the maximum operating ac stresses for practical cryogenic insulation systems are 3 to 5 kV/mm for pressurized LHe and between 5 to 10 kV/mm for pressurized LN_2.

Ageing Behavior:

Ageing is generally defined, in broad terms, as changes that take place with time that leads to a loss of life or dielectric strength. The stresses can be physical, electrical, mechanical, radiation or thermal, although the latter should not necessarily be a major factor in considering insulation for cryogenic application.

Different polymers having different chemical structures will be expected to respond differently to identical stresses and this is indeed the case.

An example would be polyethylene and polystyrene being subjected to radiation. The former would undergo crosslinking and degradation at an absorbed dose that would have little or no effect on the latter.

Factors influencing ageing at elevated temperatures are different from those at cryogenic conditions. To gain a handle on this subject it will be necessary to gather information from the literature on low temperature properties of polymers of interest, relate this information to polymer macro and microstructure, determine what ageing information at low temperatures exist, and then extrapolate the information using good technical judgment.

Radiation Resistance:

High-energy radiation causes bond cleavage in polymers, which can lead to either crosslinking (increased molecular weight) or degradation (decreased molecular weight). Other potential effects include gas evolution, or double bond formation. These chemical changes, in turn, lead to changes in physical and mechanical properties such as tensile strength or elongation.

Due to the high molecular weight, relatively low radiation doses may lead to rather large changes in physical properties of polymers used for electrical insulation. The specific changes will depend upon the nature of polymers itself and the presence of organic or inorganic additives.

For all polymers employed as electrical insulation certain additives can be incorporated that will facilitate crosslinking and enhanced physical properties. It should be noted that temperature, the physical state of polymer, the presence of oxygen, and dose rate all affect the results in a quantitative fashion.

The resistance of all polymers to radiation depends on the polymer type, the presence of organic or inorganic additives; their nature, presence of oxygen. Clearly, it is not possible to simply name a polymer and define its radiation resistance without knowing a great deal about its prior history.

Electrical Breakdown Characteristics:

The potentially wide application of superconductors in the range of cryogenic temperatures in electrical energy generation, conservation, transport and in superconducting magnet technologies requires sufficient knowledge about the breakdown mechanisms of insulating structures, depending on the cooling process. So breakdown investigations are carried out in deeply cooled gaseous helium, super fluid helium and LHe as well as LN_2 for dc, ac and impulse voltages. Besides liquids and gases, the breakdown of solid insulations of various kinds is increasingly of interest. This is directed on to spacers, tapes, low loss papers etc.

APPENDIX-II

Dielectric Behavior of Insulating Materials under Liquid Nitrogen

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ABSTRACT

Measurements were made to assess the ac breakdown voltages in liquid nitrogen (LN_2) with different electrode configurations such as sphere-sphere, needle-needle, hemisphere-hemisphere, plane-plane, sphere-needle, etc. Experimental results reveal that the breakdown voltage is a function of electrode geometry and gap length. This study also addresses the effect on the breakdown strength of solid insulating materials under LN_2 environment with a sphere - sphere electrode configuration. In this paper special emphasis has been attributed to the effect on loss index of a variety of dielectrics dipped in LN_2. The measured values of breakdown strength and loss index have been compared with those obtained under atmospheric condition. The study reveals that the breakdown strength of cellulosic materials like paper or pressboard increases manifold while the loss index decreases significantly when dipped in LN_2 with variations of the order of 50% to 90%. However, for impervious non-cellulosic materials like Perspex (acrylic glass) or presspahn the increase in breakdown strength is not that pronounced and the decrease in loss index is of the order of 2 to 30%.

1 INTRODUCTION

THE discovery of high temperature superconductivity (HTSC) in 1986, sparked a fresh interest in research in this area so that they are put to industrial applications [1-4]. In practical HTSC devices, equipment and systems, use of liquid nitrogen (LN_2) as a coolant as well as an insulating medium is essential. A lot of work has already been done to investigate various aspects of LN_2 and solid insulating materials at cryogenic temperatures regarding their electrical, mechanical, thermal, general properties, ageing effect, and radiation resistance [5-10]. However full-fledged technology is yet to be developed.

A study has been carried out to evaluate the (i) breakdown voltage of LN_2 and its dependence on various electrode configurations, (ii) breakdown strength of different solid dielectrics immersed in LN_2 and (iii) loss index of different solid dielectrics immersed in LN_2. The data presented in this paper and the earlier results [11] will contribute to the understanding of the dielectric properties, particularly the loss index of solid insulating materials in LN_2. This might lead to the selection of the desired characteristics and insulating materials to be used for insulating high temperature superconductors.

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2 EXPERIMENTAL SET-UP

2.1 AC BREAKDOWN VOLTAGE IN LN_2

Figure 1 shows various electrode geometries used for the breakdown voltage measurements in LN_2. Different combinations of electrodes such as sphere-sphere, sphere-needle, needle-needle etc. were used for obtaining the breakdown voltage of LN_2 with gap lengths varying from 1 to 5 mm.

2.2 BREAKDOWN STRENGTH OF SOLID DIELECTRICS IMMERSED IN LN_2

Figure 2 shows the schematic of a sphere-sphere electrode configuration mounted in a cryostat vessel with the test sample sandwiched between them. Both spherical electrodes were 12.5 mm in diameter. The electrodes used were made of brass. They were polished, buffed and cleaned with benzene and ethanol. While handling care was taken to keep the electrode surfaces untouched and free from scratches, dust and other impurities. The electrodes were mounted horizontally in a cryostat vessel and were cleaned and dried before each set of measurements. The applied voltage was 50 Hz, ac obtained from 150 kV, 30 kVA testing transformer which is discharge free up to 100 kV. The breakdown voltages were measured with an accuracy of ±3%.

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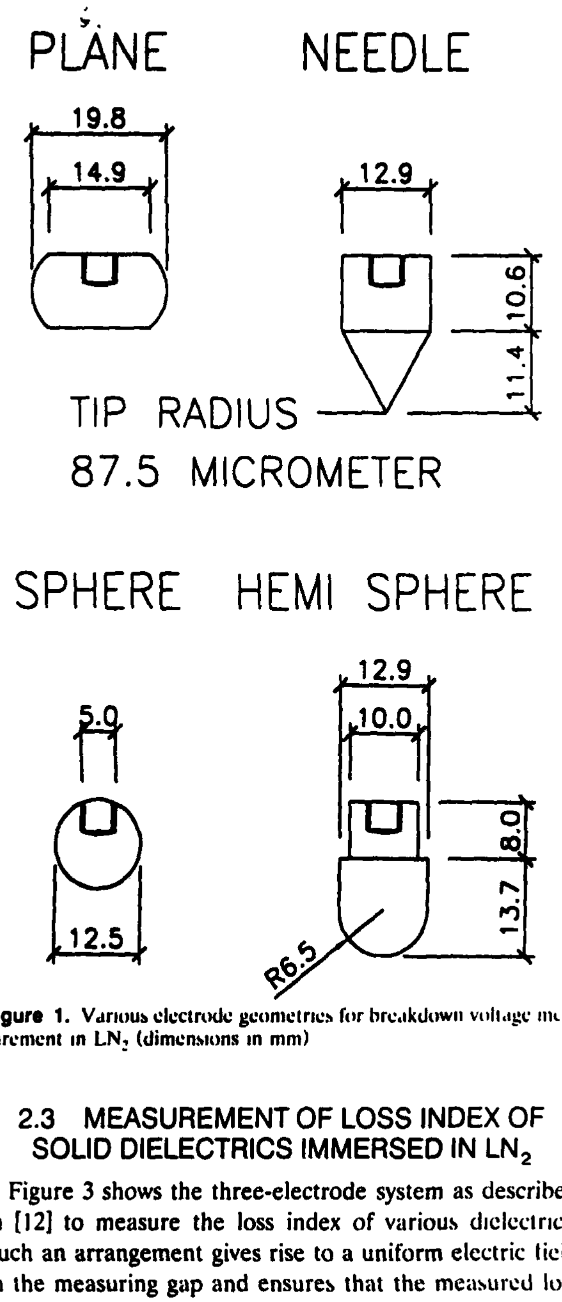

Figure 1. Various electrode geometries for breakdown voltage measurement in LN_2 (dimensions in mm)

2.3 MEASUREMENT OF LOSS INDEX OF SOLID DIELECTRICS IMMERSED IN LN_2

Figure 3 shows the three-electrode system as described in [12] to measure the loss index of various dielectrics. Such an arrangement gives rise to a uniform electric field in the measuring gap and ensures that the measured loss is accurate. The electrode surfaces were made of brass and were treated as described above to obtain a mirror finish. The electrodes were mounted vertically in a cryostat vessel and were cleaned and dried before each set of measurements. The capacitance, dissipation factor and the resistance of the dielectrics were measured using a LCR data bridge (Forbes Tinsley Co. Ltd.) with an accuracy of ±0.1%. The bridge has a capability of eliminating the effects of stray capacitances.

2.4 SAMPLE PREPARATION

Non-cellulosic dielectric samples were used without any treatment. Cellulosic solid dielectrics used as samples were treated under vacuum (100 Pa) at 100°C, for 48 h. The

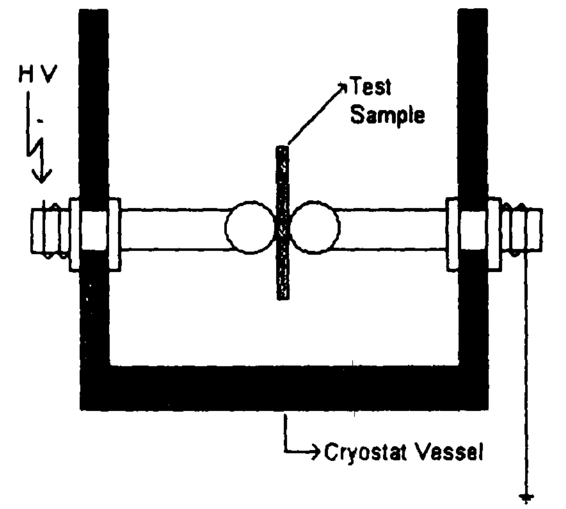

Figure 2. Schematic diagram of 12.5mm sphere-sphere electrodes mounted in a cryostat vessel

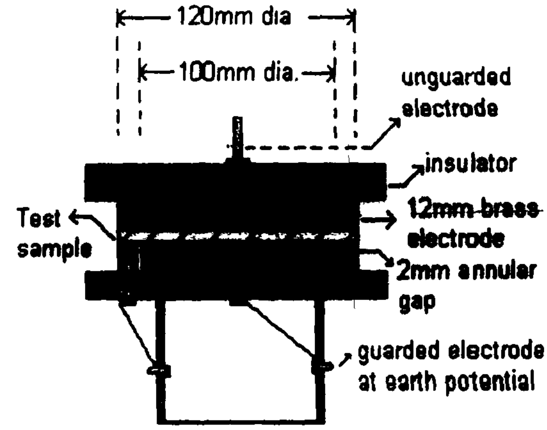

Figure 3. Three electrode system used to investigate the relative permittivity and loss tangent

sample thickness was measured at some randomly distributed 20 points, spread all over the sheet area with a micrometer having a least count of 0.01 mm. The average of the 20 measurements was taken as the average thickness of the sample.

2.5 TREATMENT OF THE CRYOSTAT VESSELS

Initially the cryostat vessels used for the above experiments were cleaned with LN_2. After a thorough cleaning, the cryostat was filled with LN_2 with a purity of 99.9% until the electrode assembly was completely filled. Measurements were initiated only after bubbling in the LN_2 completely stopped and the temperature of the liquid in the cryostat stabilized. The temperature was measured using a Chromel-Alumel thermocouple, which is suitable for a temperature range of –200°C to 1370°C with an accuracy of ±0.1°C.

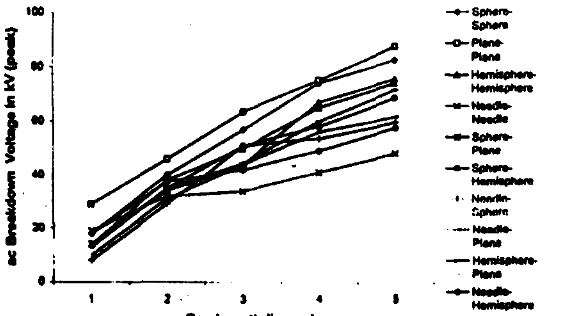

Figure 4. Breakdown voltage of LN_2 vs gap length for different electrode configurations.

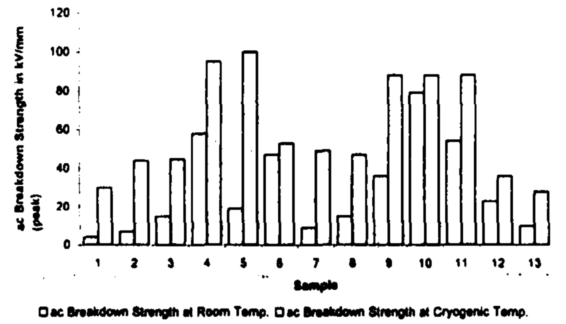

Figure 5. Comparison of ac breakdown strength of various solid dielectrics in LN_2 and in air using 12.5 mm spherical electrodes. Sample numbers are identified in Table 1.

3 RESULTS

Figure 4 shows the variation of the ac breakdown voltage in LN_2 with gap length for different electrode configurations. Each point on the curve represents an average of 20 breakdown measurements. For clarity, the deviations in measurements are not shown in Figure 4 but for most of the measurements the standard deviation was ± 2.4 kV. However for the needle - needle electrode geometry the standard deviation was found to be ± 3.7 kV. The experimental values, reported earlier [8], are in agreement with values reported in [13] for needle - plane electrode configuration using dc.

The breakdown strength of solid dielectrics measured at room temperature (27°C to 29°C) and when immersed in LN_2 are given in Table 1 and Figure 5. The reported breakdown strength is the average value of 20 measurements with a standard deviation of ± 2.7. The results are quite in agreement with the measurements as in [9,10].

Figures 6 to 14 illustrate the measured relative permittivity and loss index of various dielectrics immersed in LN_2. These values are compared with the relative permittivities and loss indices for the same set of dielectrics at room temperature. Each bar chart is a representation of the average values of ten samples of each dielectric tested in LN_2 and in air. The standard deviations in all measurements were ± 0.24 for the relative permittivity and ± 0.09 for the loss index.

4 DISCUSSIONS

4.1 AC BREAKDOWN STRENGTH OF LN_2

The highest breakdown strength of LN_2 was found to be 29 kV/mm for plane-plane electrodes configuration, while the minimum strength observed was 9.6 kV/mm for needle-needle configuration (Figure 4). The other combinations of electrodes yielded intermediate values of dielectric strength depending upon the field condition. It appears that the breakdown strength values obtained are non-intrinsic to LN_2 and are averaged by the presence of ionic impurities and very fine particles of ice, which may get introduced during the filling up of the cryostat. It is observed that, in LN_2 also, the breakdown strength goes on decreasing as the gap length increases, for example for plane-plane electrodes the breakdown strength decreases from 29 kV/mm to 18 kV/mm when the gap length changes from 1 mm to 5 mm. This effect is most pronounced in the case of the needle-needle configuration. Hence it can be inferred that the ac breakdown strength of liquid nitrogen depends not only on gap length but also on the electrode geometry, a phenomena commonly observed in gases and other liquid dielectrics [14].

Table 1. AC breakdown strength of various solid dielectrics in LN_2 and in air using 12.5 mm spherical electrodes.

Sample Number	Insulating Material	Breakdown Strength at Room Temperature (kV/mm)	Breakdown Strength at Cryogenic Temperature (kV/mm)
1	Cotton tape	4	30
2	Empire tape	7	44
3	Kraft paper	15	45
4	Polyester film	58	95
5	Leatheroid paper	19	100
6	Tyvek	47	53
7	Varnished paper	9	49
8	Bakelite	15	47
9	Mica sheet	36	88
10	Minimax	79	88
11	PVC tape	54	88
12	Perspex	23	36
13	Cable PVC	10	28

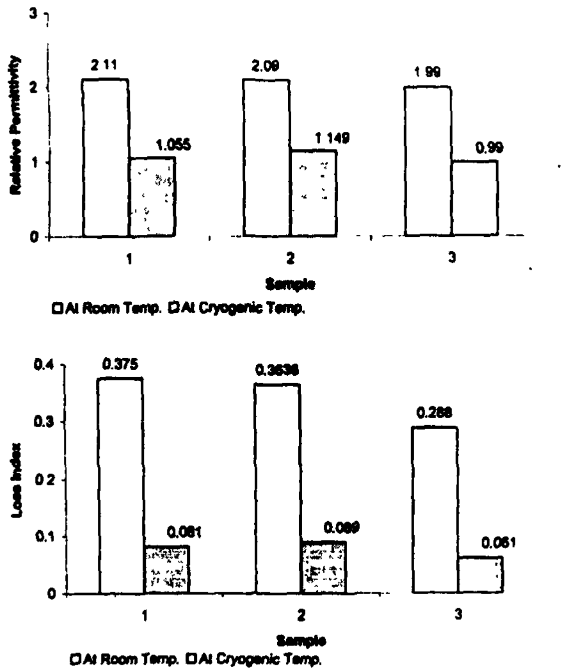

Figure 6. Comparison of relative permittivity and loss index of Crepe Paper (material density 0.9gm/cm^3) in air and in LN_2.

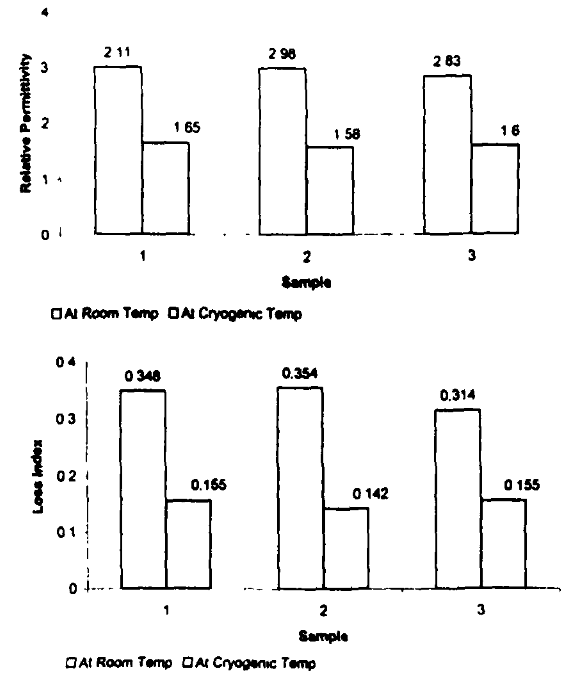

Figure 8. Comparison of relative permittivity and loss index of Pressboard-I (material density 1.28gm/cm^3) in air and in LN_2.

4.2 BREAKDOWN STRENGTH OF SOLID DIELECTRICS IMMERSED IN LN_2

Breakdown strength of solid insulating materials was found to improve when dipped in liquid nitrogen with significant increases being observed for porous materials such as Cotton tape, Empire tape, Kraft paper, Leatheroid paper, Varnished paper while the increase in the breakdown strength was comparatively low for non-porous materials like PVC tape, Minimax, Perspex, Tyvek, Mica sheet, PVC sheet of cable and Polyester film with the only exception being Bakelite.

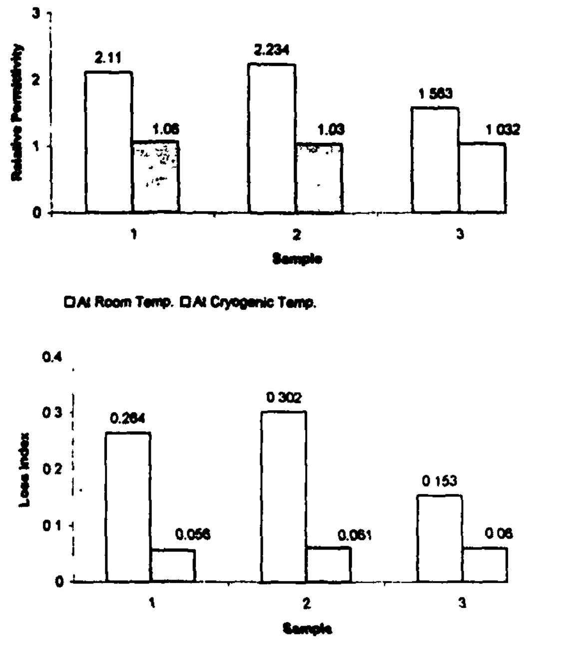

Figure 7. Comparison of relative permittivity and loss index of Kraft Paper (material density 1.01gm/cm^3) in air and in LN_2.

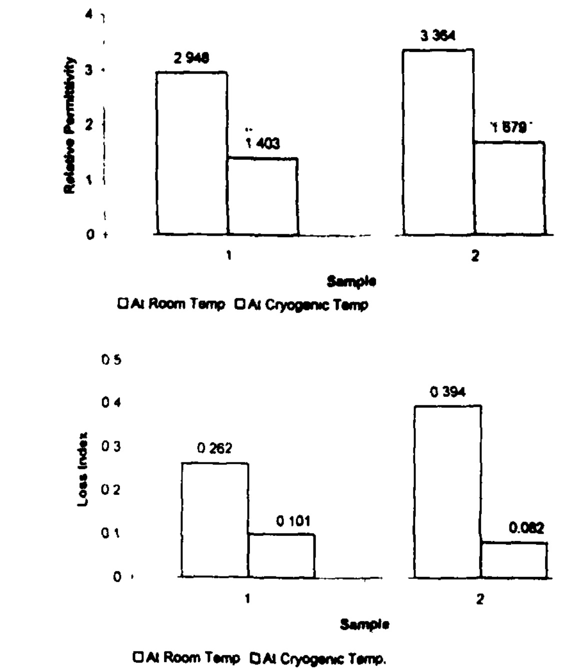

Figure 9. Comparison of relative permittivity and loss index of Pressboard-II (material density 1.15gm/cm^3) in air and in LN_2.

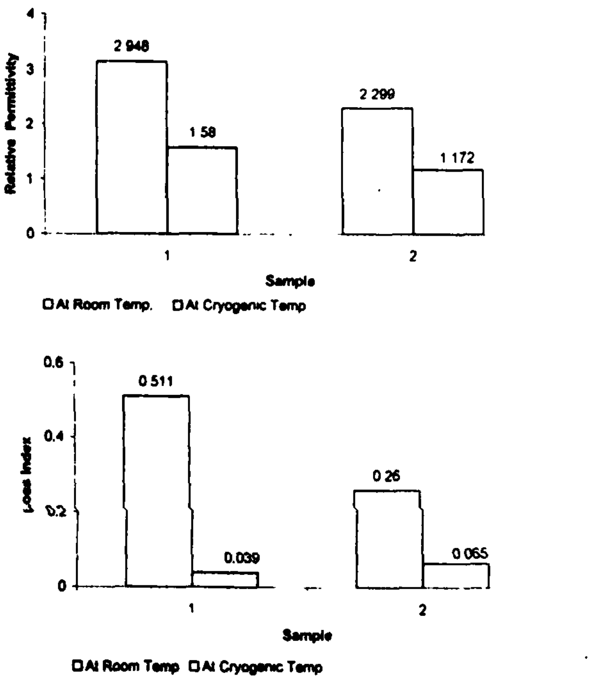

Figure 10. Comparison of relative permittivity and loss index of Pressboard-III (material density 1.04gm/cm^3) in air and in LN_2.

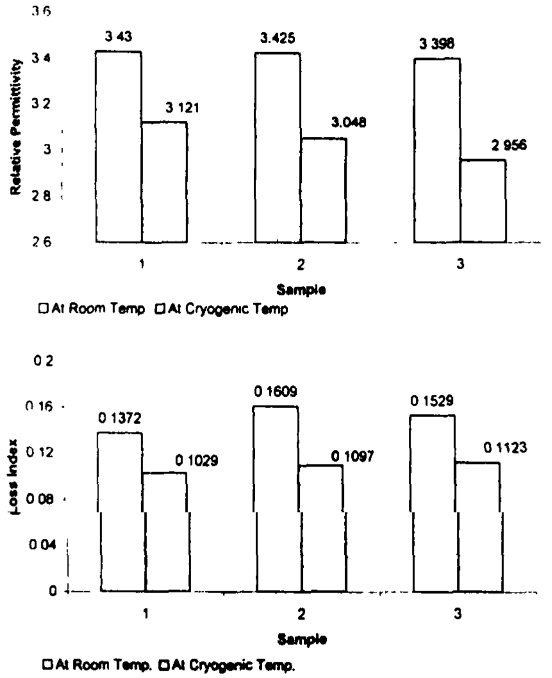

Figure 12. Comparison of relative permittivity and loss index of Perspex in air and in LN_2.

It is seen that the breakdown strength of dielectric materials in LN_2 is highly dependent on the porosity or material density of the samples. Thus, the observed results may be broadly divided into two groups, i.e. the breakdown strength of porous materials and breakdown strength of non-porous impervious materials in LN_2. For porous materials, LN_2 performs the role of impregnating the dielectrics, filling up the cavities and voids, thereby enhancing the breakdown strength. Since the relative permittivity of LN_2 is in the range of 1.3–1.4 and it fills the void /cav-

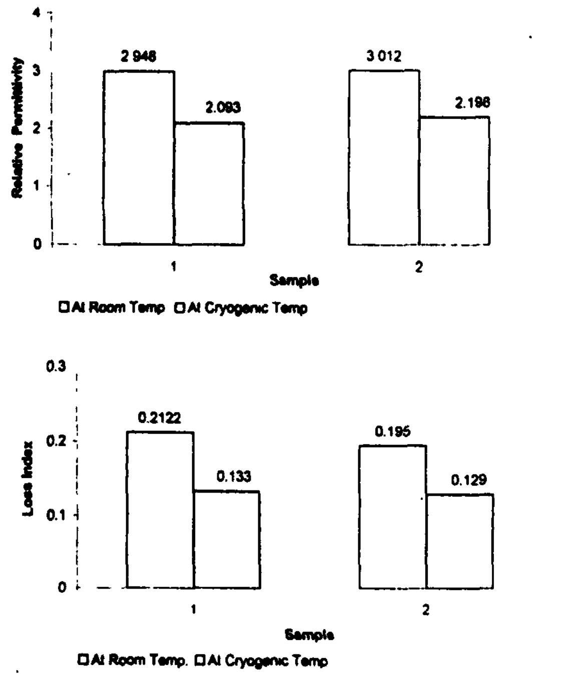

Figure 11. Comparison of relative permittivity and loss index of Polythene coated paper in air and in LN_2.

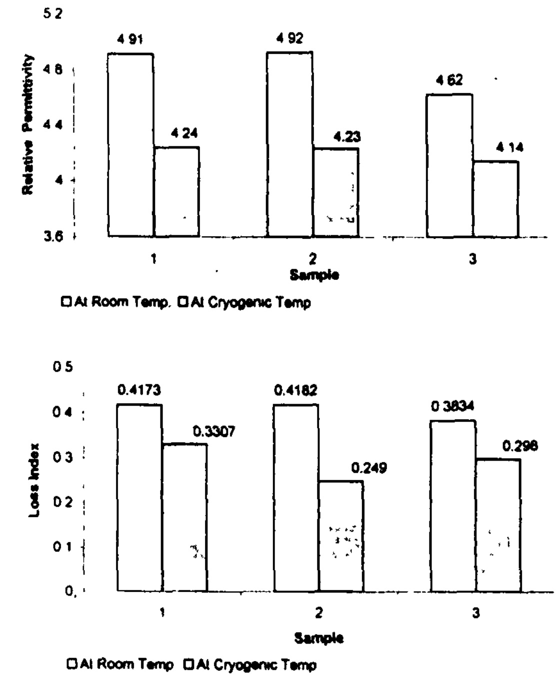

Figure 13. Comparison of relative permittivity and loss index of Thermoplastic (Nylon 6) in air and in LN_2.

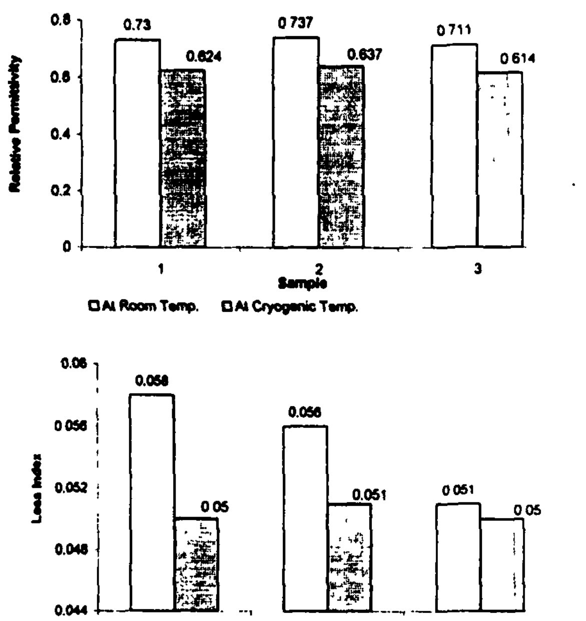

Figure 14. Comparison of relative permittivity and loss index of Presspahn in air and in LN_2.

ity at exceedingly low temperature, where the ionic mobility is also very low, resulting in higher breakdown strength. In case of nonporous materials the increase in breakdown strength is not so significant and it may be due to lowering of the temperature only.

4.3 RELATIVE PERMITTIVITY AND LOSS INDEX OF SOLID DIELECTRICS IMMERSED IN LN_2

The values of the relative permittivity and loss index measured for a variety of dielectrics are presented in Figures 6 to 14. It is known that LN_2 is a non-polar liquid and exhibits very low but measurable loss tangent of the order of 10^{-5} at power frequency.

The dielectric loss in liquids or solids or in their combination may be associated with one or more of the following mechanisms (i) dipole relaxation (ii) space charge or interfacial polarization and (iii) ionic oscillation [15]. The loss due to the first two mechanisms is a function of frequency and temperature while the loss due to ionic oscillation depends on the type of dielectric, its thickness and ionic mobility. LN_2 being a non-polar liquid, is not expected to show any dielectric loss at power frequencies. However, Jefferies and Mathes [16], measured the dielectric loss of LN_2 and found it to be practically constant for large gaps. This loss is mainly due to the presence of ionic impurities and fine particles of ice, which are difficult to avoid during the filling up process of the cryostat. However, once a solid dielectric is dipped in LN_2 the quantum of dielectric loss of the composite system will attain a value which shall lie between the limits imposed by loss index of LN_2 on one side and loss index of solid dielectric on the other. The loss index will depend on dipole relaxation and interfacial polarization. The extent of the loss will also depend on the type of dielectric and its properties namely porosity, material density and whether the solid dielectric is polar or non-polar, of course the effect being pronounced for polar dielectrics.

An examination of Figures 6 to 14 shows that in general the decrease in the dielectric loss index is two fold under LN_2 environment i.e. due to reduction in both relative permittivity and loss tangent. The percentage reduction in loss index for solids dipped in LN_2 is more for cellulosic insulating materials as compared to impervious materials.

Figures 6 to 10 represent the loss index of crepe paper, Kraft paper and pressboard with material densities 0.9, 1.01, 1.28 to 1.04 g/cm^3, respectively. It is observed that the lower is the material density, the more pronounced is the reduction in the measured loss index. This can be explained on the basis of extent of impregnation by LN_2. Further, the reduction may be attributed to a change in the lattice structure due to low temperature of LN_2 and due to formation of ice of the residual moisture present in the sample.

Figures 11 to 14 represent the loss index of polythene-coated paper, Perspex, thermoplastic (nylon 6) and presspahn. In these cases the decrease in the loss index of dielectrics dipped in LN_2 is not so pronounced because LN_2 remains only on the surface and is not able to impregnate the dielectrics.

In general it may be concluded that the relative permittivity and loss tangent of the solid dielectrics decrease when they are dipped in LN_2 but the amount of the decrease is a function of porosity and material density of the dielectric.

5 CONCLUSION

In summary, the data presented demonstrate the behavior of solid dielectrics in LN_2 environment with particular reference to the effect on their breakdown strength and loss index. The data presented and analyzed recommend the use of porous dielectrics for insulating high temperature superconductors. However a more comprehensive study is desired regarding partial discharge phenomena, mechanical and thermal characteristics and aging process of solid insulants dipped in LN_2, in order to predict the breakdown strength.

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APPENDIX III

BREAKDOWN OF CRYOGENIC AIR UNDER NON-UNIFORM FIELDS

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With the discovery of High Temperature Superconductors in 1986, researchers have developed prototypes of High Temperature Superconductor based power equipment such as transformers, current limiters, superconducting cables etc. In most of these prototypes liquid nitrogen (LN_2) has been used as a coolant and insulant to maintain the temperature of High Temperature Superconductor at about 77 °K. In practical apparatus cryogenic gas will coexist with LN_2. Therefore, the knowledge of gas characteristics at cryogenic temperature is essential.

Keeping the above in view, experiments were designed to measure the ac breakdown voltages of air at room temperature as well as at cryogenic temperature under non –uniform field conditions using coaxial cylinders of different dimensions. The results so obtained have been analyzed and correlated using field utilization factor U with earlier reported results under uniform field conditions. This study leads to the fact that air at cryogenic temperature cannot be substitute for liquid nitrogen.

Keywords Cryogenic, uniform field, non-uniform field, field utilization factor, spherical electrodes, coaxial cylinder electrode.

1. INTRODUCTION

Superconducting technologies have rapidly developed in recent years, and they are expected to be applied to electrical power engineering in the near future. Cryogenic liquids are claimed to have a note-worthy impact on the concept of improved future power equipment using High Temperature Superconductors [1].

In designing superconducting electrical apparatus, the knowledge of cryogenic gas and LN_2 insulation characteristics is essential [2-3]. Also it is important to study the breakdown characteristics of cryogenic air and the effect of field geometry.

The 50 Hz breakdown voltages in air at room temperature and air at cryogenic temperature under uniform field conditions have been reported earlier [2-5]. When non-uniform field conditions exist, it should be possible to evaluate the breakdown voltage using the breakdown voltages under uniform field conditions and vice-versa.

For practical use in non-uniform fields, a field utilization factor U can be obtained and breakdown voltage under non-uniform field conditions can be calculated as a fraction of the uniform field breakdown voltage under similar conditions of gap and pressure [4-6].

Numerous studies [2-5] have already been carried out under uniform as well as non-uniform field conditions using different dielectrics at cryogenic temperature. It seems that little efforts are made to correlate these results.

The aim of this study is to find the 50 Hz breakdown voltages in air at room temperature (295° K, 744 mm Hg) and air at cryogenic temperature under non-uniform field conditions using coaxial geometry and relate them with the data reported earlier for uniform field conditions [2].

2. EXPERIMENTAL SETUP

Figure1 shows the schematic of the coaxial cylinder electrode configuration used. The outer conductor radius R_o was 18 mm. The radius of the inner conductor R_i was varied from 0.75 mm to 3.0 mm.

The electrodes used were made of brass. They were polished, buffed and cleaned with benzene and ethanol. While handling the electrodes, extreme care was taken not to cause scratches and keep the electrodes free from dust and other impurities.

Two sets of coaxial cylinders identical in all respects, one for studying the ac breakdown voltages and the other for monitoring the temperature, were mounted horizontally in the cryostat vessel.

The 50 Hz voltage was obtained from 150 kV, 30 kVA testing transformer which was discharge free upto 100 kV. The breakdown voltages were measured with an accuracy of ± 3%. The temperatures were measured using a Chromel-Alumel thermocouple, which is suitable for a temperature range of 73°K to 1643°K with an accuracy of ± 0.1°C.

Initially, the cryostat vessel used for the above experiments was cleaned with LN_2. After a thorough cleaning, the cryostat was filled with LN_2 of 99.9% purity until the electrode assembly was completely dipped in LN_2.

Measurements were made only after bubbling in the LN_2 completely stopped and the temperature of the LN_2 in the cryostat stabilized to 83°K and the temperature of air in the coaxial cylinder provided with temperature probe stabilized to 96°K.

3. RESULTS

Table I shows the ac breakdown voltages in air at room temperature and cryogenic temperature observed in the laboratory using coaxial geometry for different gap lengths (R_o - R_i) between inner and outer conductors. Each observation represents an average of 10 breakdown voltages. For clarity, the deviations in measurements are not shown, but for most of the measurements the standard deviations was ± 1.2 kV.

4. DISCUSSIONS AND CONCLUSIONS

The ac breakdown voltages observed for air at cryogenic temperature under non-uniform field conditions show only a slight improvement (10-20%) over the breakdown voltage for air at room temperature. This may be accounted for by reduced mobility of the carriers at cryogenic temperature.

Sphere-to-Sphere gaps less than their radii spark approximately at the same potential as uniform field gaps. In case of coaxial electrode system having inner and outer electrode radii of R_i and R_o respectively the field utilization factor is given by

$$U= R_i/(R_o-R_i)^* \ln [R_o/R_i]$$

It has been shown earlier [6] that the effect of field utilization factor can be evaluated by measuring the sparking potentials in uniform and non-uniform fields under similar conditions. Also for practical use in a non-uniform field in which the field utilization factor is U, the sparking potential was obtained as a fraction $f = U^{0.85}$ of the uniform field sparking potential for the same gap under similar conditions of gas [6].

Table II shows the breakdown voltages in air at room temperature reported earlier by Ritz [5] and with spherical electrodes as reported by Toyota [2].

Table III shows the breakdown voltages in air at cryogenic temperature using spherical electrodes [2] and also values after multiplication by $U^{0.85}$. The Table III also gives a comparison of the values obtained in the laboratory using coaxial cylinders.

These breakdown voltages for uniform fields multiplied by the field utilization factor are evaluated and compared with the results obtained for non-uniform fields and have been plotted in Figures 2 and 3 respectively. It is observed that the application of field utilization factor $U^{0.85}$ holds good even for air at cryogenic temperature.

The breakdown strength of air at cryogenic temperature (Table I) is quite low as compared to breakdown strength of liquid nitrogen [3]. It suggests that the, insulation of high temperature superconductors with cryogenic air offers no advantages when compared to high temperature superconductors insulated with liquid nitrogen due to superior breakdown strength of LN_2 as reported in a recent study [3]. However, it may be easy to maintain the temperature and pressure of air in the cylinder when compared to direct LN_2 cooling.

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Figure 1 Coaxial Cylinder Geometry.

(All dimensions are in mm.)

Figure 2 Breakdown Voltage Vs. Gap in air at room temperature.

Figure 3 Breakdown Voltage Vs. Gap in air at cryogenic temperature.

Table I AC Breakdown voltages in air at room temperature and at cryogenic temperature.

(R_o= 18mm and R_i = 0.75, 0.9, 1.15, 1.32, 1.475, 1.625, 1.8, 2.0, 2.75 and 3.0 mm)

Table II Breakdown voltages (Ritz uniform fields, Toyota sphere to sphere, Ritz and Toyota's non-uniform and observed values in the laboratory) in air at room temperature

Table III Breakdown voltage (Toyota's sphere to sphere, Toyota's non-uniform and observed values in the laboratory) in air at cryogenic temperature.

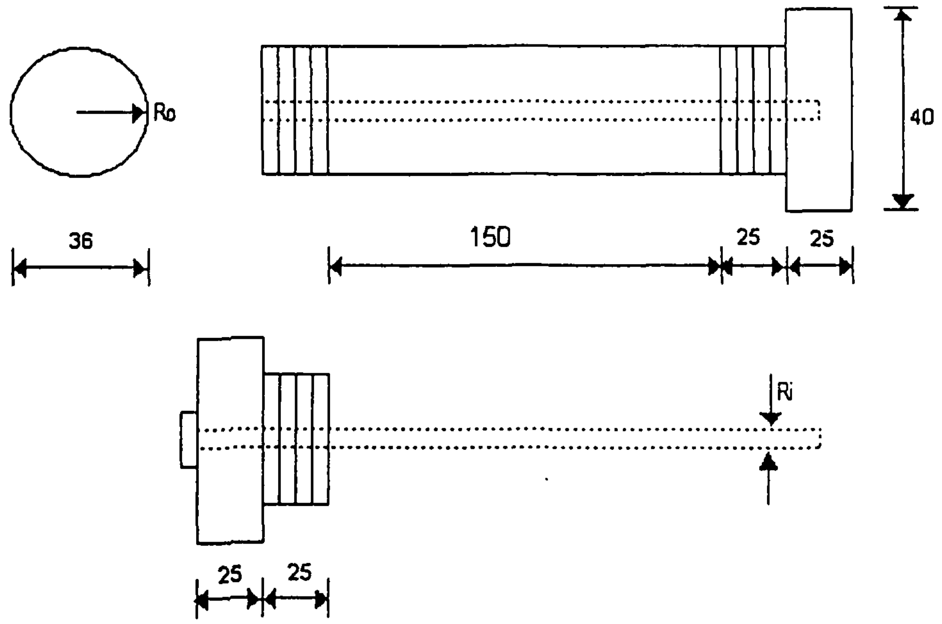

Figure 1

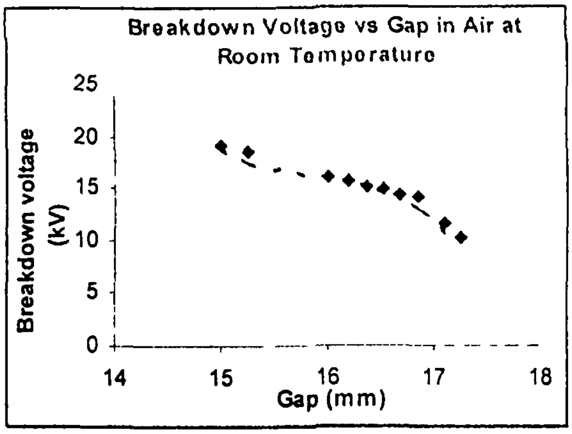

Figure 2

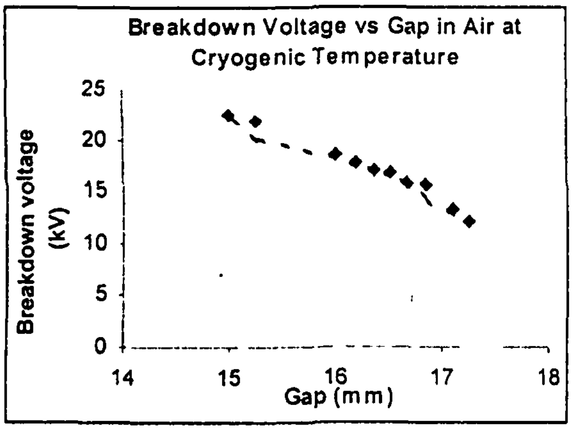

Figure 3

Table I

S.No.	Gap (mm) $G=(R_o - R_i)$	Breakdown voltage (kV) <u>Air at room temperature</u>	Breakdown voltage (kV) <u>Air at cryogenic temperature</u>
1.	17.25	10.1	12.03
2.	17.10	11.5	13.20
3.	16.85	14.1	15 66
4.	16.68	14.2	15.80
5.	16.52	14.9	16.85
6.	16.37	15.1	17.03
7.	16.20	15.6	17.78
8.	16.00	16.1	18.50
9.	15.25	18.6	21.92
10.	15.00	19.1	22.43

TABLE II

S.No.	GAP (mm) $G=R_o-R_i$	RITZ Uniform Field BDV (kV)	Toyota Sp.to Sp. BDV (kV)	$U^{0.85}$	$BDV_{co\text{-}axial}$ (kV)		
					RITZ[5] RITZ* $U^{0.85}$	Toyota [2] Toyota * $U^{0.85}$	Observed in the laboratory
1.	17.25	51.17	50.570	0.186	09.52	09.60	10.1
2.	17.10	50.76	50.170	0.208	10.56	10.54	11.5
3.	16.85	50.49	49.495	0.242	12.01	11.88	14.1
4.	16.68	49.61	49.036	0.262	13.00	12.75	14.2
5.	16.52	49.10	48.604	0.279	13.72	13.61	14.9
6.	16.37	48.78	49.199	0.296	14.44	13.98	15.1
7.	16.20	48.30	47.740	0.314	15.17	14.80	15.6
8.	16.00	47.75	47.200	0.334	15.95	15.58	16.1
9.	15.25	45.71	45.175	0.399	18.24	18.10	18.6
10.	15.00	45.03	44.500	0.418	18.82	18.69	19.1

TABLE III

S.No.	GAP (mm) $g=R_o-R_i$	Toyota Sp.to Sp. BDV (kV)	$U^{0.85}$	$BDV_{coaxial}$ (kV)	
				Toyota Sp.to Sp. * $U^{0.85}$	Observed in the laboratory
1.	17.25	58.13	0.186	11.04	12.03
2.	17.10	57.75	0.208	12.13	13.20
3.	16.85	57.13	0.242	13.71	15.66
4.	16.68	56.70	0.262	14.74	15.80
5.	16.52	56.30	0.279	15.76	16.85
6.	16.37	55.93	0.296	16.22	17.03
7.	16.20	55.50	0.314	17.21	17.78
8.	16.00	55.00	0.334	18.15	18.50
9.	16.25	53.13	0.399	21.25	21.92
10.	15.00	52.50	0.418	22.05	22.43